3-22-2019

Near Real-Time RF-DNA Fingerprinting for ZigBee Devices Using Software Defined Radios

Frankie A. Cruz

NEAR REAL-TIME RF-DNA FINGERPRINTING FOR ZIGBEE DEVICES USING SOFTWARE DEFINED RADIOS

THESIS

Frankie A. Cruz, Captain, USAF

AFIT-ENG-MS-19-M-021

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT-ENG-MS-19-M-021

NEAR REAL-TIME RF-DNA FINGERPRINTING FOR ZIGBEE DEVICES USING SOFTWARE DEFINED RADIOS

THESIS

Presented to the Faculty

Department of Electrical Engineering

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

in Partial Fulfillment of the Requirements for the

Degree of Master of Science in Computer Engineering

Frankie A. Cruz, B.S.E.E.

Captain, USAF

March 21, 2019

AFIT-ENG-MS-19-M-021

NEAR REAL-TIME RF-DNA FINGERPRINTING FOR ZIGBEE DEVICES USING SOFTWARE DEFINED RADIOS

THESIS

Frankie A. Cruz, B.S.E.E.
Captain, USAF

Committee Membership:

Maj J. Addison Betances, PhD
Chair

Dr. Michael A. Temple
Member

Dr. Timothy H. Lacey
Member

AFIT-ENG-MS-19-M-021

Abstract

Low-Rate Wireless Personal Area Network(s) (LR-WPAN) usage has increased as more consumers embrace Internet of Things (IoT) devices. ZigBee Physical Layer (PHY) is based on the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 specification designed to provide a low-cost, low-power, and low-complexity solution for Wireless Sensor Network(s) (WSN). The standard's extended battery life and reliability makes ZigBee WSN a popular choice for home automation, transportation, traffic management, Industrial Control Systems (ICS), and cyber-physical systems. As robust and versatile as the standard is, ZigBee remains vulnerable to a myriad of common network attacks. Previous research involving Radio Frequency-Distinct Native Attribute (RF-DNA) Fingerprinting and device discrimination has shown that bit-level WSN security can be augmented with PHY-based features. The objective of this research was to develop and implement an Radio Frequency (RF) air monitor system that classifies devices in Near Real-Time (NRT). The performance of the NRT air monitor is contrasted against previous research that utilized MATLAB-based Fingerprinting post-processing RF-DNA.

The RF air monitor demonstration included collection of IEEE 802.15.4 bursts from $N_d = 10$ RZUSBsticks to assess NRT performance and effectiveness. The first set of experiments examined how well the air monitor recovered IEEE 802.15.4 data packets while fingerprinting and discriminating ZigBee devices under two distinct workloads. The second set of experiments compared predictive post-processed MATLAB RF-DNA Multiple Discriminant Analysis/Maximum Likelihood (MDA/ML) models Average Percent Correct Classification ($\%C$) against the air monitor's observed operational $\%C$ for each RZUSBstick. The air monitor achieved an Overall Acurate Packet Reconstruction

Percent (%R) $\geq$ 97.92% while correctly fingerprinting an Overall Fingerprinted Percent (%F) $\geq$ 97.48% of the transmitted IEEE 802.15.4 data packets during the trials. The air monitor achieved an overall operational %$C \approx$ 96.93% at a collected Signal-to-Noise Ratio (SNR) $\approx$ 33.571 dB, classified each RZUSBstick within 0.45 msec $\leq T_{\text{MDA}} \leq$ 1.5 msec after detection, and %C Deviation (%C_{Δ}) = 2.71% from the collected post-processed MDA/ML model. The results support that an RF air monitor is feasible, can be effective, and will accurately operate within predictive post-processed MATLAB model estimations.

Acknowledgements

I would like to thank my wife and children, I wouldn't be where I am today without thier love and support. I would also like to thank Major Betances for his guidance and mentoring throught my tenure at AFIT.

Frankie A. Cruz

Table of Contents

List of Figures

List of Tables

List of Abbreviations

$\%A_{\Delta}$	Absolute Reconstructed Packet Ratio Deviation
AFIT	Air Force Institute of Technology
AWGN	Additive White Gaussian Noise
BPSK	Binary Phase Shift Keying
BPSK	Binary Phase Shift Keying
CB-DNA	Constellation Based-Distinct Native Attributes
CM	Confusion Matrix
CPM	Continuous Phase Modulation
CRC	Cyclic Redundancy Check
$\%C$	Average Percent Correct Classification
$\%C_{\Delta}$	$\%C$ Deviation
ACK	acknowledgement
DNA	Distinct Native Attribute
DDR3	Double Data Rate Type 3 Synchronous Dynamic Random-Access Memory
DDR3L	Low Voltage Double Data Rate Type 3 Synchronous Dynamic Random-Access Memory
DS	Data Symbol(s)
DSSS	Direct Sequence Spread Spectrum

DSP Digital Signal Processing

FIFO First-In-First-Out

GUI Graphical User Interface

GPL GNU General Public License

GPU Graphics Processing Unit

ICS Industrial Control Systems

IIR Infinite Impulse Response

I In-Phase

M&M Mueller and Müller

IoT Internet of Things

Q Quadrature-Phase

I/Q In-Phase and Quadrature-Phase

$\%I$ Individual % Incorrect Classification

IEEE Institute of Electrical and Electronics Engineers

$\Im$ Imaginary

IIR infinite impulse response

ITU-T International Telecommunication Union - Telecommunication Standardization Sector

LR-WPAN Low-Rate Wireless Personal Area Network(s)

MDA Multiple Discriminant Analysis

MAC Media Acess Control Layer

ML Maximum Likelihood

MDA/ML Multiple Discriminant Analysis/Maximum Likelihood

MODEM Modulator/Demodulator

MSK Minimum Shift Keying

NRT Near Real-Time

O-QPSK Offset-Quadrature Phase Shift Keying

OOT Out-of-Tree

OS Operating System

PHY Physical Layer

PHR PHY Header

QPSK Quadrature Phase Shift Keying

$\Re$ Real

ROI Region of Interest

PMF Probability Mass Function

$\%D$ Overall Packet Detection Percent

$\%R$ Overall Acurate Packet Reconstruction Percent

$\%F$ Overall Fingerprinted Percent

PPDU PHY Protocol Data Unit

PSDU PHY Service Data Unit

PRNG Pseudo Random Noise Generated

PHR PHY Header

RF Radio Frequency

RX Receive

RF-DNA Radio Frequency-Distinct Native Attribute

ROI Region(s) of Interest

SD Spectral Domain

SNR Signal-to-Noise Ratio

SDR Software-Defined Radio(s)

SFD Start-of-Frame Delimiter

SHR Synchronization Header

SNA Sensor Network Analyzer

SN Serial Number

SSD Solid State Drive

TD Time Domain

USRP Universal Software Radio Peripheral(s)

USB Universal Serial Bus

uInt32 32-Bit Unsigned Integer

WPAN Wireless Personal Area Network(s)

WSN Wireless Sensor Network(s)

NEAR REAL-TIME RF-DNA FINGERPRINTING FOR ZIGBEE DEVICES USING SOFTWARE DEFINED RADIOS

I. Introduction

This chapter provides the operational and technical motivations for conducting this research. Section 1.1 describes the operational motivation for looking into the ZigBee protocol. Section 1.2 provides the technical motivation to fingerprint and discriminate ZigBee devices in Near Real-Time (NRT). Section 1.3 concludes Chapter I with the organizational details for the remainder of this document.

1.1 Operational Motivation

ZigBee is an Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 based standard ideal for low-data rate applications that require an extended battery life and reliable networks. As such, ZigBee Wireless Personal Area Network(s) (WPAN) have gained popularity to the point were they have become the de facto standard for Wireless Sensor Network(s) (WSN) [1]. ZigBee network's low-cost, low-power, and low-complexity make them a popular choice for home automation, transportation, traffic management, and Industrial Control Systems (ICS). These advantages come with a heightened risk of unauthorized data access and modifications to ZigBee networks. Some of these risks include rogue devices, replay attacks, network key sniffing, spoofing, and denial of service attacks [2–4]. Digital communication systems typically implement security mechanisms using bit-level credentials and validity checks to guard against such attacks. This research focuses on leveraging unique properties within

Physical Layer (PHY) waveform transmissions as an additional layer of security to complement traditional security measures.

1.2 Technical Motivation

There has been an extensive amount of research conducted at the Air Force Institute of Technology (AFIT) investigating techniques to augment the security of numerous communication systems by exploiting features found in the PHY [5–19]. Part of AFIT's research portfolio includes using Radio Frequency-Distinct Native Attribute (RF-DNA) fingerprinting as an effective a method to augment the security of ZigBee based networks. RF-DNA Fingerprinting generates human-like "fingerprints" from a device's PHY waveform to attain a unique one-to-one association between a fingerprint and a device. This makes RF-DNA difficult to mimic and serves as an effective method to classify various devices. While RF-DNA classification has shown to be effective, a majority of the previous experiments have been implemented in the form of MATLAB based post-processing This research is an initial step towards the ultimate goal of demonstrating an autonomous low-cost, compact, stand-alone Radio Frequency (RF) air monitor. This will be accomplished by implementing an air monitor composed of an Software-Defined Radio(s) (SDR) loaded with a trained Multiple Discriminant Analysis/Maximum Likelihood (MDA/ML) model; assessing the air monitor's NRT fingerprinting and discrimination performance; and comparing the air monitor's results to MATLAB results.

1.3 Document Organization

The remainder of this document is organized as follows:

- Chapter II - Background: Provides a brief overview of the ZigBee protocol, the modulation methods involved to process ZigBee transmissions, RF-DNA finger-

printing, the MDA/ML process, and the hardware and software utilized throughout this research.

- Chapter III - Methodology: Provides the methodology used for experimental signal collection, the SDR design, the two fingerprinting generation methods, and the MDA/ML process and data generation.

- Chapter IV - Analysis of Results: Provides results and analysis of the air monitor's performance during high disk usage; the air monitor's performance loaded with trained MDA/ML data; the estimative and actual MDA/ML models; and NRT device discrimination results.

- Chapter V - Conclusion: Provides a summary and conclusions based on research results and recommendations for future research.

II. Background

This chapter provides background on the methods used in this research supporting Chapter III and the interpretation of the results generated in Chapter IV. Section 2.1 provides a brief overview of the ZigBee protocol defined by the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 standard for Wireless Personal Area Network(s) (WPAN) [20]. Section's 2.2 and 2.3 provide a general overview of Offset-Quadrature Phase Shift Keying (O-QPSK) and Minimum Shift Keying (MSK) modulation. Section 2.4 goes over Radio Frequency-Distinct Native Attribute (RF-DNA) Fingerprinting which consists of extracting statistical features from specified Region(s) of Interest (ROI) in the time-domain. Section 2.5 covers model development and device classification using a Multiple Discriminant Analysis/Maximum Likelihood (MDA/ML) process. Section 2.6 describes equipment used to isolate Radio Frequency (RF) signals. Section 2.7 describes KillerBee, a security research toolkit specifically designed to explore, evaluate, and exploit IEEE 802.15.4 based networks. Section 2.8 covers Wireshark, a network protocol analyzer to inspect packets [21]. Section 2.9 briefly covers the Cyclic Redundancy Check (CRC)-16 error-checking used in this research. This is followed by a very brief description of a C++ based linear algebra library in Section 2.10. Section 2.11 goes over the Software-Defined Radio(s)s (SDRs) used in this research. Chapter II wraps up with Section 2.12 which describes GNU Radio, an open-source SDR framework [22].

2.1 ZigBee

ZigBee is an IEEE 802.15.4 based standard for very low-cost, low-data rate, low-power WPAN [20, 23]. ZigBee devices are utilized for consumer electronics, home and building automation, industrial controls, PC peripherals, and medical sensors in both

military and civilian applications [1, 20, 23]. The IEEE 802.15.4 Physical Layer (PHY) has several modulation standards for various frequencies, but this research is focused on O-QPSK modulated frequency bands which will be explained in Section 2.2 [20, 23].

The IEEE 802.15.4 O-QPSK PHY supports three frequency bands: a 16-channel 2450.0 MHz band; a 10-channel 915.0 MHz band; and a 1-channel 868.0 MHz band. All the previously mentioned IEEE 802.15.4 bands utilize Direct Sequence Spread Spectrum (DSSS) Modulator/Demodulators (MODEMs) [1, 23]. The 2450 MHz band was utilized to conduct all of the experiments for this research. The 16 channels for the 2450 MHz band have a center frequency that can vary between 2405.0 MHz $\leq f_{rng} \leq$ 2480.0 MHz [1, 23]. The standard specifies the center frequency f_C for each of the 16 channels as [1]:

$$f_C = [2405 + 5(k-11)] \text{ MHz, for } k = 11, ..., 26 \tag{2.1}$$

Each channel is separated by $\Delta_{Ch} = 5.0$ MHz with an instantaneous bandwidth of $f_{BW} = 2.0$ MHz and intra-channel gap-bands of $f_{gap} = 3.0$ MHz [1, 23]. The center frequencies and bandwidth utilization are illustrated in Figure 2.1.

ZigBee incorporates DSSS by mapping 4-bit segments to one of sixteen Data Symbol(s) (DS) [23]. Each DS is then mapped to a nearly orthogonal 32-bit sequence as shown in Table 2.1 [1, 23]. The even DS bits are mapped to the In-Phase (I) component of the O-QPSK signal and the odd DS bits are mapped to the offset Quadrature-Phase (Q) component of the O-QPSK signal [1, 23]. Previous research conducted by

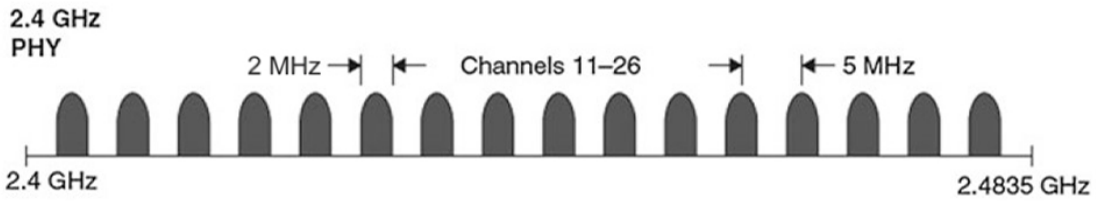


Figure 2.1. Frequencies and Channel Spread for ZigBee in the 2450.0 MHz Band [1]

Dr. Thomas Schmidt demodulated IEEE 802.15.4 signals using a non-coherent receiver employing MSK [24]. Section 2.3 has more details on about how to implement MSK as a special case of O-QPSK [24, 25]. Demodulating IEEE 802.15.4 with a non-coherent receiver with MSK will change two components. First, the DSSS mapping sequence will be different than the O-QPSK as shown on Table 2.2. Second, the first demodulated DSSS chip is always set to a "don't care" value because the I bit will be unknown and both In-Phase and Quadrature-Phase (I/Q) chips are needed to determine the proper value of the first chip [24].

ZigBee devices operating in the 2450.0 MHz band have a data rate (R_b), DS symbol rate (R_{DS}), chip-rate (R_c), O-QPSK symbol rate ($R_{\text{O-QPSK}}$) as follows:

$$\begin{aligned} R_b &= 250.0 \text{ kBits/sec} \\ R_{\text{DS}} &= 62.5 \text{ kSym/sec} \\ R_c &= 2.0 \text{ Mc/sec} \\ R_{\text{O-QPSK Sym}} &= 1.0 \text{ MS/sec} \end{aligned} \tag{2.2}$$

Section 2.2 provides additional information about O-QPSK modulation scheme. Figure 2.2 provides an overall illustration of the ZigBee DSSS process along with each symbols corresponding 32-Bit Unsigned Integer (uInt32) value [1, 23].

Per the IEEE 802.15.4 standard, the O-QPSK PHY Protocol Data Unit (PPDU) consists of a Synchronization Header (SHR) that is used to synchronize to a data stream; a PHY Header (PHR) containing the frame length; and a variable length PHY Service Data Unit (PSDU) that contains the remaining data and sublayer [1, 9, 23]. The SHR is composed of a preamble sequence consisting of 4 bytes of 0x00 and a Start-of-Frame Delimiter (SFD) byte of `0x7A` (or `b1110 0101`) marking the end of the SHR [23]. This

Table 2.1. ZigBee Symbol-to-Chip Mapping for the O-QPSK 2450.0 MHz Band [20, 24]

Symbol	Chip sequence (C0, C1, C2, ... , C31)	uInt32 value
0	11011001110000110101001000101110	3653456430
1	11101101100111000011010100100010	3986437410
2	00101110110110011100001101010010	786023250
3	00100010111011011001110000110101	585997365
4	01010010001011101101100111000011	1378802115
5	00110101001000101110110110011100	891481500
6	11000011010100100010111011011001	3276943065
7	10011100001101010010001011101101	2620728045
8	10001100100101100000011101111011	2358642555
9	10111000110010010110000001110111	3100205175
10	01111011100011001001011000000111	2072811015
11	01110111101110001100100101100000	2008598880
12	00000111011110111000110010010110	125537430
13	01100000011101111011100011001001	1618458825
14	10010110000001110111101110001100	2517072780
15	11001001011000000111011110111000	3378542520

Table 2.2. ZigBee Symbol-to-Chip Mapping for the MSK 2450.0 MHz Band [24]

Symbol	Chip sequence (C0, C1, C2, ... , C31)	uInt32 value
0	x11000000111011110101110011011 00	1618456172
1	x10011100000011101111010111001 10	1309113062
2	x11011001110000001110111101011 10	1826650030
3	x11001101100111000000111011110 10	1724778362
4	x01011100110110011100000011101 11	778887287
5	x11110101110011011001110000001 11	2061946375
6	x11101111010111001101100111000 00	2007919840
7	x00001110111101011100110110011 10	125494990
8	x00111111000100001010001100100 11	529027475
9	x01100011111100010000101000110 01	838370585
10	x00100110001111110001000010100 01	320833617
11	x00110010011000111111000100001 01	422705285
12	x10100011001001100011111110001 00	1368596360
13	x00001010001100100110001111110 00	85537272
14	x00010000101000110010011000111 11	139563807
15	x11110001000010100011001001100 01	2021988657

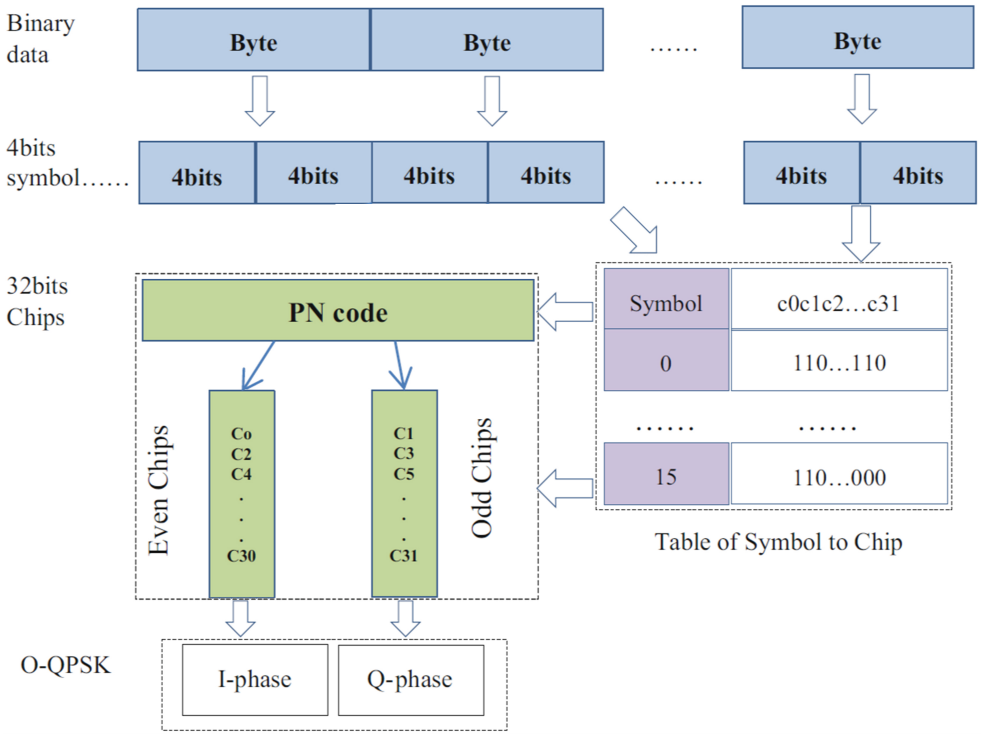


Figure 2.2. Flowchart of ZigBee's DSSS Implementation [1]

research was accomplished by segregating devices based on the statistical data gathered from the waveform containing the SHR of each device. Sections 2.4 and 2.5 cover how each device was identified using statistical data. Figure 2.3 shows a complete IEEE 802.15.4 PPDU packet.

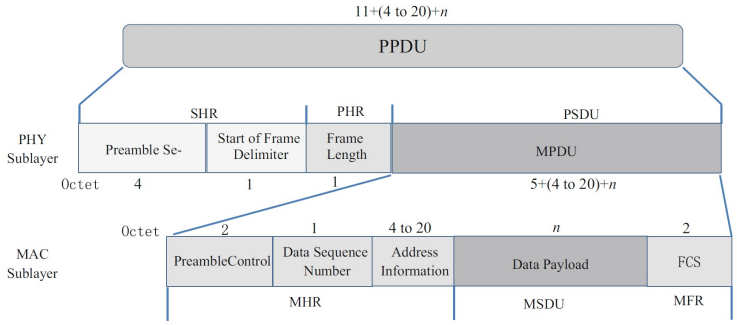


Figure 2.3. PPDU Frame Format [1, 9, 23]

2.2 O-QPSK Modulation

Quadrature Phase Shift Keying (QPSK) modulation consists of two independent Binary Phase Shift Keying (BPSK) signals: an I signal and a Q signal [25]. QPSK divides a binary input data stream $d_{Data}(t) = d_0, d_1, d_2, ...$ to separate channels representing 1 or 0 as bipolar pulses where $d_{Data} = \pm 1$ [25]. The even data bits are inserted onto the I data stream and the odd bits do the same on the Q data stream as shown on (2.3) and (2.4) [25].

$$d_I(t) = d_0, d_2, d_4, ... \text{(even bits)} \tag{2.3}$$

$$d_Q(t) = d_1, d_3, d_5, ... \text{(odd bits)} \tag{2.4}$$

The $d_I(t)$ and $d_Q(t)$ data streams are modulated onto the I and Q portions of the carrier wave as follows [25]:

$$s(t) = \frac{1}{\sqrt{2}} d_I(t) cos\left(2\pi f_0 t + \frac{\pi}{4}\right) + \frac{1}{\sqrt{2}} d_Q(t) sin\left(2\pi f_0 t + \frac{\pi}{4}\right), \tag{2.5}$$

where f_0 represents the carrier frequency in Hz.

Since the I and Q QPSK data streams are orthogonal to each other, the two data streams can be demodulated separately [25]. Using the trigonometric identities, QPSK can be be written in the following form:

$$s(t) = cos\left(2\pi f_o t + \theta(t)\right), \quad \text{where } \theta = \left[0, \frac{\pi}{2}, \frac{3\pi}{2}, \pi\right]. \tag{2.6}$$

O-QPSK is equivalent to QPSK waveforms in that both modulation schemes share the same constellation symbols and can also be represented by (2.5) [25]. What sets O-QPSK and QPSK apart is that QPSK can transition from one symbol to any other symbol as shown in Figure 2.5, while O-QPSK can only make a transition to adjacent symbols (i.e. $\Delta\theta \in [-\pi/2, 0, \pi/2,]$) as shown on Figure 2.6 [25]. This is accomplished

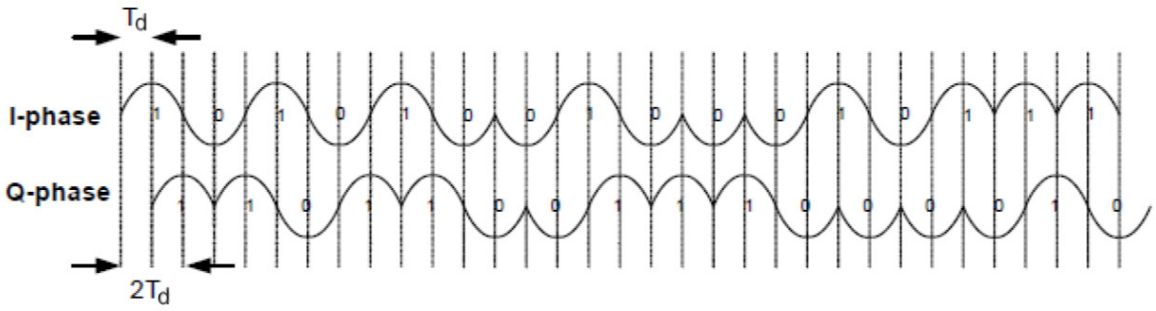


Figure 2.4. O-QPSK I/Q Waveform with Time Offset T_d [23, 25]

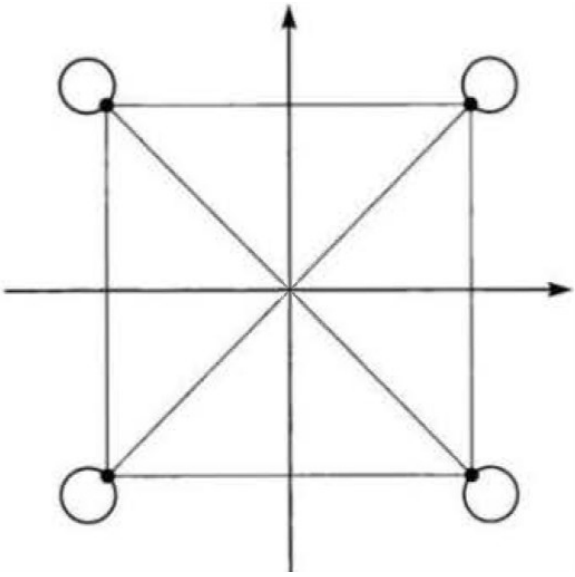


Figure 2.5. QPSK Phase Transition Diagram [26]

by adding a time offset T_d that is equal to half of the symbol period $T_{\text{O-QPSK}}$. The I and Q data streams are represented on Figure 2.4.

2.3 MSK Modulation

MSK is a form of Continuous Phase Modulation (CPM) that can be viewed as a special case of O-QPSK with sinusoidal symbol weighting [25]. MSK data encoding using sinusoidal symbol weighting can be represented as

$$s(t) = d_I(t)cos\left(\frac{\pi t}{2T}\right)cos\left(2\pi f_0 t\right) + d_Q(t)sin\left(\frac{\pi t}{2T}\right)sin\left(2\pi f_0 t\right), \tag{2.7}$$

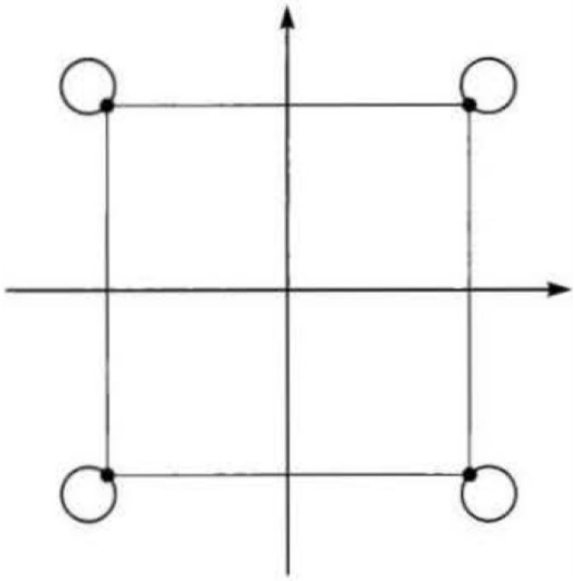


Figure 2.6. O-QPSK Phase Transition Diagram [26]

with $d_I(t)$ and $d_Q(t)$ using the same data stream as (2.3) and (2.4).

2.4 RF-DNA Fingerprinting

Fingerprinting is a method of creating a mathematical profile of a device based on collected emissions. Factors that influence each device's fingerprint include operating temperature, device age, tolerances, and variations in manufacturing [5, 8–10, 27]. RF-DNA fingerprints can be generated from Time Domain (TD) or Spectral Domain (SD) responses. This research effort focused on TD fingerprints and do not address SD responses. The fingerprints are generated using the instantaneous amplitude (a), instantaneous phase (ϕ), and instantaneous frequency (f) responses of a specified ROI. The ROI is broken down into N_R subregions where each instantaneous feature is assessed. Individual instantaneous features are calculated within an ROI subregion N_R containing N_s complex samples of equal sample length as

$$N_s = \lfloor \text{length}(\text{ROI}) / N_R \rfloor. \tag{2.8}$$

With the N_s samples in each subregion N_R, each instantaneous feature is calculated using the Real ($\Re$) and Imaginary ($\Im$) components from $\mathbf{x}[n]$ as follows [9]:

Instantaneous Amplitude (a)

$$\mathbf{a}[n] = \sqrt{\Re(\mathbf{x}[n])^2 + \Im(\mathbf{x}[n])^2}, \qquad n = \{0, 1, 2, ..., N_s - 1\}, \tag{2.9}$$

Instantaneous Phase (ϕ)

$$\phi[n] = \tan^{-1}\left(\frac{\Im(\mathbf{x}[n])}{\Re(\mathbf{x}[n])}\right), \quad \Im(\mathbf{x}[n) \neq 0, \quad n = \{1, 2, ..., N_s - 1\}, \tag{2.10}$$

Instantaneous Frequency (f)

$$\mathbf{f}[n] = \frac{d\phi[n]}{d[n]}, \quad n = \{0, 1, 2, ..., N_s - 1\}. \tag{2.11}$$

Previous research has shown that an IEEE 802.15.4 SHR waveform serves as an ideal ROI since the waveform within the SHR contains the same first 5 bytes (10 DSSS symbols) for every transmitted burst [9, 16].

The sequences from (2.9) through (2.11) are adjoined subregions from the ROI and summarized using $N_M = 3$ statistical metrics of variance (σ^2), skewness (γ), and kurtosis (κ) for each N_R subregion that are calculated from,

$$\mu = \frac{1}{N_s - 1} \sum_{n=0}^{N_s-1} \mathbf{x}[n]. \tag{2.12}$$

$$\sigma^2 = \frac{1}{N_s - 1} \sum_{n=0}^{N_s-1} (\mathbf{x}[n] - \mu)^2, \tag{2.13}$$

$$\gamma = \frac{1}{(N_s - 1)\sigma^3} \sum_{n=0}^{N_s-1} (\mathbf{x}[n] - \mu)^3, \tag{2.14}$$

$$\kappa = \frac{1}{(N_s-1)\sigma^4}\sum_{n=0}^{N_s-1}(\mathbf{x}[n]-\mu)^4, \tag{2.15}$$

and used to form the ROI subregion vector as

$$\mathbf{F}_{R_i} = [\sigma^2, \gamma, \kappa]_{1\times 3}. \tag{2.16}$$

The full-dimensional time domain fingerprint N_{TD} is composed of N_R subregions, N_F instantaneous features per subregion, and N_M statistical metrics per instantaneous TD feature as shown on (2.17) and (2.18). Figure 2.7 is a summarized overview of RF-DNA TD Fingerprinting.

$$\mathbf{F}_{\text{TD}} = \left[\mathbf{F}^1 \vdots \mathbf{F}^2 \ldots \vdots \mathbf{F}_F^N\right]_{[1\times N_M \times N_R \times N_F]} = \left[\mathbf{F}^{\text{a}} \vdots \mathbf{F}^{\phi} \vdots \mathbf{F}^{\text{f}}\right]_{[1\times N_M \times N_R \times 3]} \tag{2.17}$$

$$\mathbf{N}_F = [1 \times N_M \times N_R \times N_F] \tag{2.18}$$

2.5 MDA/ML

Fingerprints are created specifically to classify and discriminate between devices based on statistical metrics. Multiple Discriminant Analysis (MDA) and Maximum Likelihood (ML) processing effectively classifies and maximizes device discrimination with provided fingerprints. First part of the process begins with MDA reducing input feature dimensionality by projecting N_F input features into a N_C-1 subspace where it is assumed that $N_F \geq N_C$ and N_C >2 in an attempt to maximize between-class dimensional spread and minimize within-class dimensional spread. The between-class (S_b) and within-class (S_w) scatter matrices are computed as,

$$\mathbf{S}_b = \sum_{i=1}^{N_C}\mathbf{P}_i\Sigma_i, \tag{2.19}$$

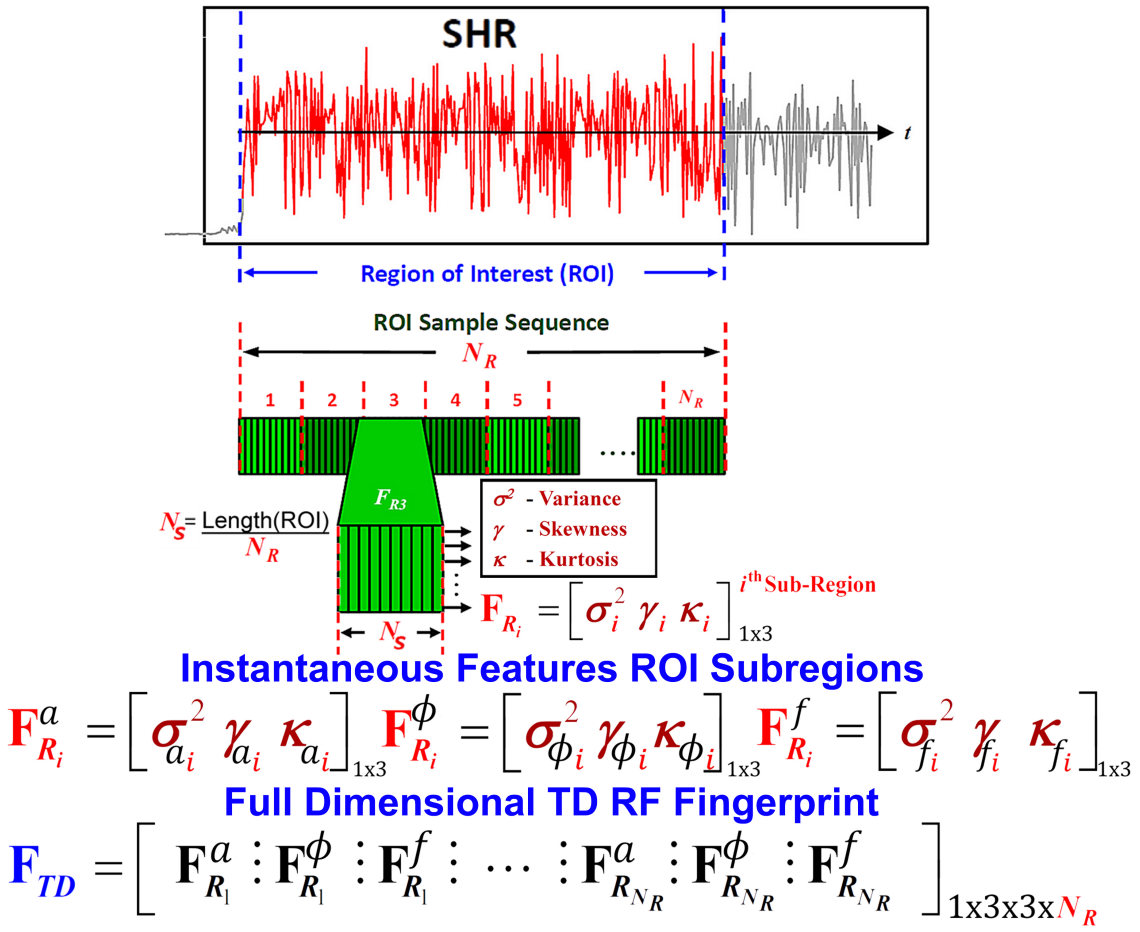


Figure 2.7. Summarized Overview of RF-DNA TD Fingerprinting [14, 27]

$$\mathbf{S}_w = \sum_{i=1}^{N_C} \mathbf{P}_i \left(\mu_i - \mu_0\right)\left(\mu_i - \mu_0\right)^T, \tag{2.20}$$

with class covariance(Σ_i) and global mean (μ_0) calculated as,

$$\Sigma_i = E\left[\left(x - \mu_i\right)\left(x - \mu_i\right)^T\right], \tag{2.21}$$

$$\mu_0 = \sum_{i=1}^{N_C} P_i \mu_i, \tag{2.22}$$

where μ_i is the mean and P_i is the prior probability of each N_C class [9]. The generated $\mathbf{F}_{\text{TD}}$ RF-DNA fingerprints are projected into the $(N_C - 1)$-dimensional space in

accordance with

$$\widehat{\mathbf{f}} = \mathbf{W}^T \mathbf{F}_{\mathrm{TD}}, \tag{2.23}$$

where $\mathbf{W}$ is the $N_F \times (N_C - 1)$ projection matrix created from the $N_C - 1$ Eigenvectors of $\mathbf{S}_w^{-1}\mathbf{S}_b$ and $\widehat{\mathbf{f}}$ is the RF-DNA fingerprint projection into the lower dimensional subspace.

The effectiveness of $\mathbf{W}$ classifying devices entirely depends on how well $\mathbf{S}_b$ distance was maximized and $\mathbf{S}_w$ spread was minimized. Figure 2.8 is an example of two MDA projection matrices, $\mathbf{W}_1$ and $\mathbf{W}_2$, for $N_C = 3$ classes onto a $(N_C - 1)$-dimensional subspace with $\mathbf{W}_1$ providing the "best" classification [27].

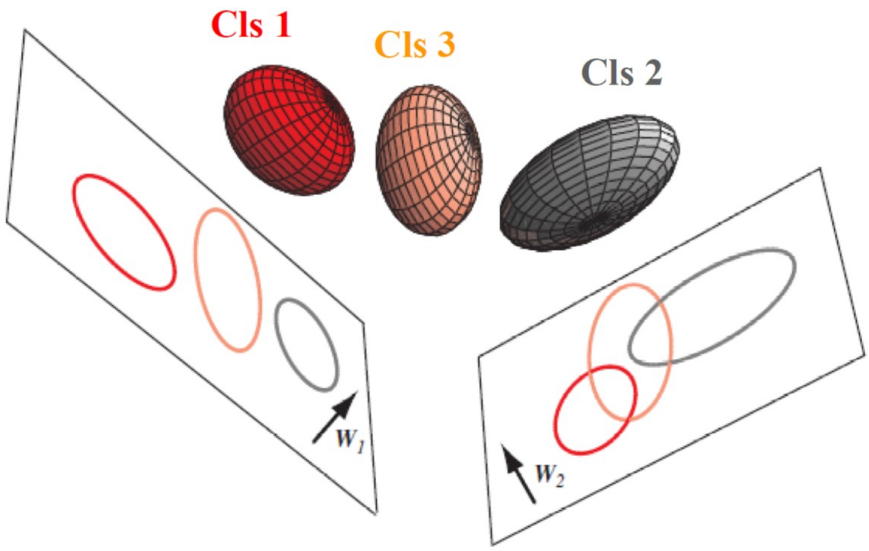


Figure 2.8. Representative MDA Projections using W_1 and W_2 for a $N_C = 3$ problem into a $(N_C - 1)$-Dimensional Space [27].

ML classification of $\widehat{\mathbf{f}}$ is implemented by performing an estimation based on Bayesian posterior probability that the conditional posterior probability $P\left(c_i|\widehat{f}\right)$ that $\widehat{f}$ belongs to class c_i where $i = 1, 2, ..., N_c$ is given as [8, 27, 28]:

$$P\left(c_i|\widehat{f}\right) = \frac{P\left(\widehat{f}|c_i\right)P\left(c_i\right)}{P\left(\widehat{f}\right)} \tag{2.24}$$

The final classification decision is made by designating the calculated $\widehat{\mathbf{f}}$ to the N_C returning the highest probable measure of similarity.

2.6 Ramsey STE4400

The Ramsey STE4400 is a portable benchtop RF Shielded test enclosure that enables testing and analysis in a tightly controlled test environment. The STE4400 provides 90 dB attenuation for signals in the 2 GHz band operating outside of the test enclosure [29].

2.7 KillerBee: ZigBee Attack Platform

KillerBee was developed by River Loop Security as a framework and toolset for attacking IEEE 802.15.4 based networks to include ZigBee [4]. KillerBee enables the ATMEL RZUSBsticks devices to transmit arbitrary ZigBee packets and/or beacon requests even when they are not operating in a network. The transmitted data can be compared against the received collections for statistical analysis and validation of results. The following KillerBee tools were leveraged for generating data [4]:

- `zbreplay` - Implements a replay attack from a specified `daintree` file or `libpcap` packet capture. acknowledgement (ACK) frames are not retransmitted.
- `zbconvert` - Convert a packet capture from `libpcap` to `daintree` Sensor Network Analyzer (SNA) format, or vice-versa.

2.8 Wireshark

Wireshark is an open-source network protocol analyzer that provides users the ability to exhaustively inspect network data in a live or off-line environment [21]. Wireshark was used as a verification tool since the software suite already has support for

both ZigBee and IEEE 802.15.4 protocols. The network traffic for a ZigBee device from the Control4® product line was stored in a `libpcap` file for use as a baseline. These network traffic was inspected with Wireshark to assess normal ZigBee traffic.

2.9 CRC-16

CRC is an error-detection code and a sub-class of linear block codes used to verify the integrity of the data [30]. The derivation of the formula is outside the scope of this thesis, but CRC works by performing polynomial long division on a set of data $d(x)$ taken as the dividend and a generator polynomial $G(x)$ as the divisor [30]. The long divisions resultant remainder $R(x)$ is the parity bit used to determine if the data is valid. IEEE 802.15.4 PSDU packets contain and make use of a 16-bit International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) CRC generator polynomial $G_{16}(x)$. The generator polynomial $G_{16}(x)$ is defined as

$$G_{16}(x) = x^{16} + x^{12} + x^5 + 1, \tag{2.25}$$

where an $R(x)$ with an odd result indicates that there is an error in the message. An CRC-16 error-check was performed on the recovered ZigBee packets in this research for statistical analysis. A complete description of the CRC-16 usage is presented in Chapter IV.

2.10 Eigen

Eigen is an open-source C++ template library for linear algebra to support matrix, vector, numerical solvers, and related operations and algorithms [31]. Eigen was used for matrix multiplication in Near Real-Time (NRT) MDA/ML that will be further expanded upon in Chapter III.

2.11 SDR

An SDR is a radio device in which some or all of the functions are software defined [32]. SDRs are extremely flexible devices that allow users to configure modulation, bandwidth, and sampling rates on the fly as opposed to purely analog devices that have a fixed configuration. An Ettus B205mini-i was used to collect ZigBee transmissions for this research. The B205mini-i has a tuning range of 70.0 MHz $\leq f_{rng} \leq$ 6.0 GHz, an instantaneous bandwidth of $f_{BW} \leq$ 56.0 MHz, and an adjustable sample rate up to $R_{Samp} = 61.44$ MS/sec with a resolution of 12-bits [33].

2.12 GNU Radio

GNU Radio is a free open-source software development kit that leverages SDRs through the use of signal processing blocks in a live or simulated environment [22]. Users have the ability to rapidly create and reconfigure a signal processing flow graph using a built-in tool called `gnuradio-companion`. `gnuradio-companion` is an Graphical User Interface (GUI) providing the ability to quickly drag-and-drop signal blocks on a flow graph and connect them together. This tool implements signal processing blocks that rivals in performance with commercial applications such as MathWorks Simulink or NI-LabVIEW. The `gnuradio-companion` flow graph generates a python file that can be further modified to further customize the generated GUI or include additional python libraries that aren't included within *gnuradio-companion*.

GNU Radio has a wide variety of common Digital Signal Processing (DSP) blocks that implements common operations encountered in digital communication systems. However, this research required a custom signal processing to generate RF-DNA fingerprints in NRT. GNU Radio's `gr_modtool` script facilitates the creation of custom block by generating templates for the required files. `gr_modtool` enables a user to create Out-of-Tree (OOT) modules that house new blocks generated in Python or C++.

The performance requirements to properly fingerprint and discriminate ZigBee bursts in NRT required the development of a C++ block.

A complete IEEE 802.15.4 SHR waveform is required to be captured accurately and processed almost immediately for NRT device discrimination. An existing OOT module developed by Dr. Bastian Bloessl was modified to capture valid SHR transmissions during DSSS demodulation [34, 35]. Another block was developed to perform NRT RF-DNA fingerprinting and MDA/ML discrimination. Chapter III elaborates the details involved in performing NRT RF-DNA fingerprinting and MDA/ML discrimination.

III. Methodology

This chapter provides the methodology used to acquire results posted in Chapter IV. Each section is presented in successive order as shown on Figure 3.1. Section 3.1 explains the GNU Radio Software-Defined Radio(s) (SDR) air monitor's physical and software receiver design. Section 3.2 provides detailed specifics on how the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 Synchronization Header (SHR) bursts were captured with the blocks described in Section 3.1.2. Section 3.3 describes the fingerprint generation process completed in MATLAB and GNU Radio. Section 3.4 specifies the devices discriminated using Multiple Discriminant Analysis/Maximum Likelihood (MDA/ML) processing and how the trained data model was applied to the blocks in Section 3.1.2.

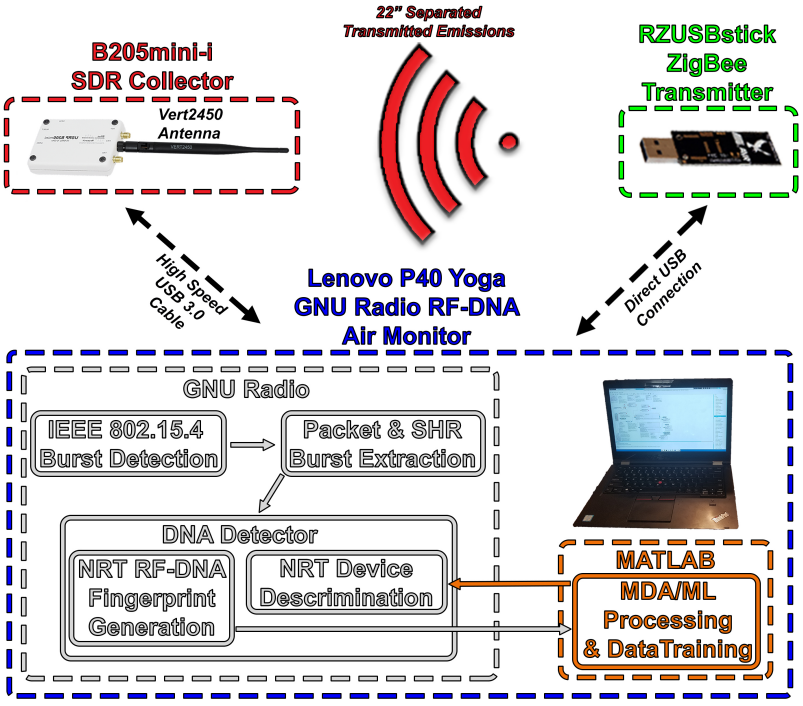


Figure 3.1. Methodology for NRT RF-DNA Fingerprinting and Device Discrimination

3.1 GNU Radio SDR Receiver Design

The hardware used by the air monitor in this research consists of an Ettus B205mini-i, a Lenovo p40 Thinkpad Yoga laptop, and various RZUSBsticks that were switched between collection and discrimination trials as illustrated on Figure 3.2. The Lenovo p40 is equipped with an Intel® Core™ i7-660 Processor, 16 GB of Low Voltage Double Data Rate Type 3 Synchronous Dynamic Random-Access Memory (DDR3L), a 1 TB Samsung 850 Pro Solid State Drive (SSD), and an NVIDIA® Quadro® M500M Graphics Processing Unit (GPU) with 2 GB of Double Data Rate Type 3 Synchronous Dynamic Random-Access Memory (DDR3). The B205mini-i was connected to the Lenovo p40 using a 4 feet Universal Serial Bus (USB) 3.0 cable capable of sustaining data rates of up to 625 MB/sec [36]. This setup enables maximum performance for the B205mini-i's since this device data rate is limited to 184.3 MB/sec as listed on Section 2.11. Each RZUSBstick had a direct connection to the Lenovo p40's USB port positioned closest to the B205mini-i. The B205mini-i and each RZUSBstick were separated by approximately 22 inches for every trial. To ensure a consistent trial setting, the locations for the Lenovo p40 and B205mini-i were marked in the test bench, and the B205mini-i was secured in place using masking tape. Table 3.1 contains the manufacturing label information for each RZUSBstick.

Ubuntu 18.04.1 LTS was the Operating System (OS) used to develop the GNU Radio air monitor and operate the tools discussed in Chapter II. GNU Radio was compiled with build version *3.14.13.4* and the B205mini-i's drivers were compiled from *release_003_011_000_1*. Refer to Ettus and GNU Radio's websites for detailed software installation instructions and the required dependencies needed for everything to work properly [22, 33]. The Eigen C++ libraries were installed alongside GNU Radio to implement linear algebra algorithms required to generate RF-DNA fingerprints and perform device discrimination. The GNU Radio modules *gr-ieee802.15.4* and *gr-*

Table 3.1. RZUSBstick's MAC Address, AT86RF230 Transceiver Marks, Device Date Code, and SN

Device	MAC ID	Mark 1	Mark 2	Date Code	Device SN
1	A0:F6:9F:E7	1442 PH	1R8338-7	2015.05.26	0200004417
2	A0:01:43:70	0923 PH	8P0772	2010.06.01	0200002338
3	A0:01:5D:34	0936 PH	9P0187-2	2015.05.26	0200004387
4	A0:F6:A0:68	1442 PH	1R8338-7	2010.05.31	0200002058
5	A0:F6:A0:4E	1442 PH	1R8338-7	2015.05.26	0200004528
6	A0:F6:9F:FF	1442 PH	1R8338-7	2015.05.26	0200004485
7	A0:F6:A0:0C	1442 PH	1R8338-7	2015.05.26	0200004488
8	A0:F6:A0:04	1442 PH	1R8338-7	2015.05.26	0200004508
9	A0:F6:9F:EA	1442 PH	1R8338-7	2015.05.26	0200004377
10	A0:F6:9F:E0	1442 PH	1R8338-7	2015.05.26	0200004416

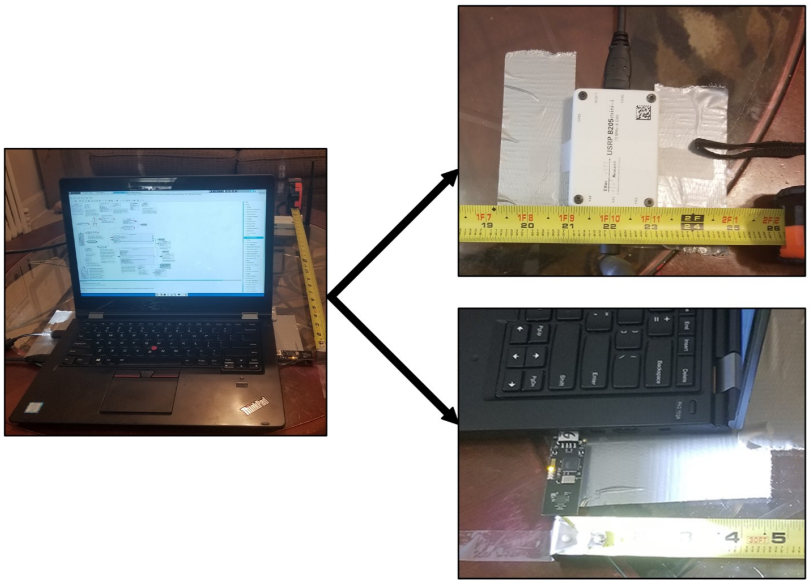


Figure 3.2. Air Monitor Test Configuration

foo contain the necessary flow graphs, blocks, and source code necessary to develop the air monitor. Both modules are publicly available under the GNU General Public License (GPL) agreement from Dr. Bastian Bloessl's GitHub repository [34, 37].

An *IEEE 802.15.4 Offset-Quadrature Phase Shift Keying (O-QPSK) Physical Layer (PHY)* transceiver block within the *gr-ieee802.15.4* module has been shown to effectively capture and process IEEE 802.15.4 packets [24, 34, 35]. Several features were extracted from the *IEEE 802.15.4 O-QPSK PHY* transceiver block's source code to ac-

curately detect and capture SHR bursts.

Additional GNU Radio blocks were added to the *gr-ieee802.15.4* module to facilitate access to the existing private functions within the *gr-ieee802.15.4* module. Section 3.1.1 explains the *IEEE 802.15.4 O-QPSK PHY* transceiver block illustrated on Figure 3.3. Figure 3.5 illustrates which sub-blocks were extracted and modified to develop the air-monitor. Section 3.1.2 provides a comprehensive overview of the RF-DNA air monitor block components.

3.1.1 *IEEE 802.15.4 PHY* Transceiver Block.

The original *IEEE 802.15.4 PHY* transceiver blocks Python source code was generated in *gnuradio-companion* with the *ieee802_15_4OQPSK_PHY.grc* flow graph file. Figure 3.4 contains the transceiver blocks which receive and transmit IEEE 802.15.4 packets as described in Sections 2.1 and 2.2. The receive blocks and its dependencies were modified to perform NRT fingerprinting and discrimination. The transceiver's receive blocks were implemented using C++ classes available from the base GNU Radio source files or the *gr-ieee802.15.4* module. Further inspection revealed that the Packet Sink block performed the Direct Sequence Spread Spectrum (DSSS) demodulation and passed IEEE 802.15.4 PHY Service Data Unit (PSDU) packets created within the block to the *rxout* asynchronous message port. Each receive block displayed in Figure 3.4 was used in creating the *RFDNA_Prototype_v1.0.grc* flow graph file for the RF-DNA air monitor.

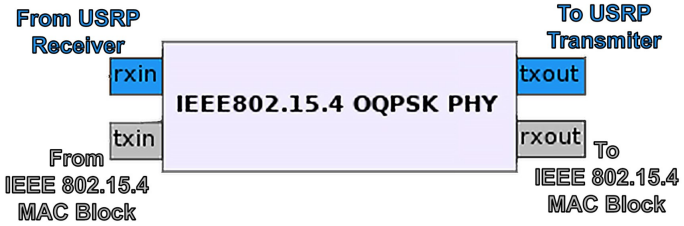


Figure 3.3. ***IEEE O-QPSK 802.15.4*** **Transceiver Block**

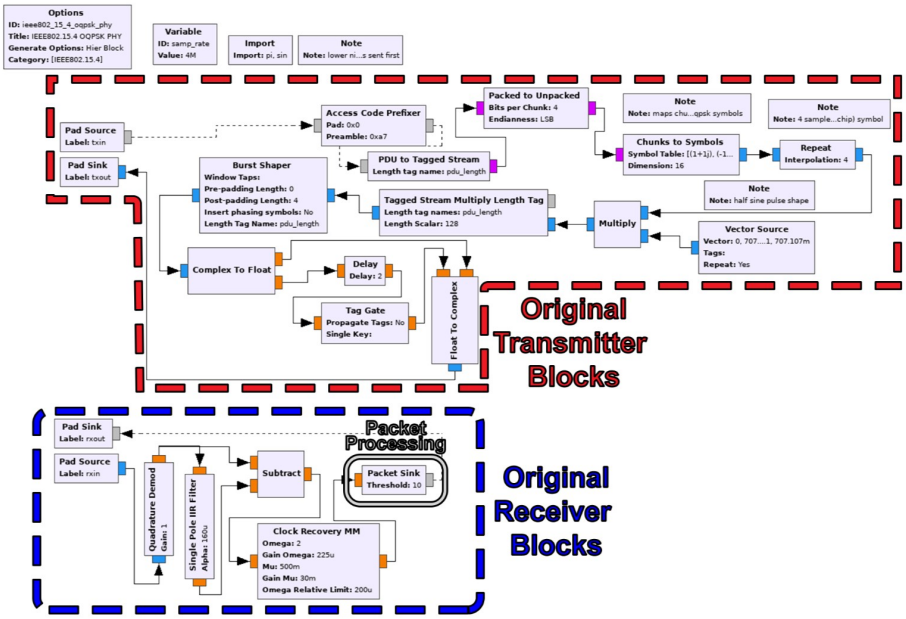


Figure 3.4. ***IEEE 802.15.4 PHY*** **Transceiver Block Flow Graph**

3.1.2 RF-DNA Air Monitor.

The RF-DNA air monitor makes use of the previous blocks extracted from the *IEEE 802.15.4 PHY* transceiver block with the *preamble_sink* block used in place of the *Packet Sink* block. The *preamble_sink* block leveraged *Packet Sink*'s source code and added several features that will be expanded upon in Section 3.1.2.4. The overall functionality of the RF-DNA air monitor can be broken down into 1) Universal Software Radio Peripheral(s) (USRP) and Receive (RX) interface, 2) demodulation and detection, 3) sample delay, 4) data visualization, and 5) data storage. Each functional section of the RF-DNA air monitor's flow graph shown on Figure 3.5 is covered sequentially from Section 3.1.2.1 to Section 3.1.2.6.

3.1.2.1 USRP RX Interface.

The USRP RX interface specifications on Figure 3.6 were kept as close as possible to the examples provided in the *gr-ieee802.15.4* module. As such, the entire flow graph

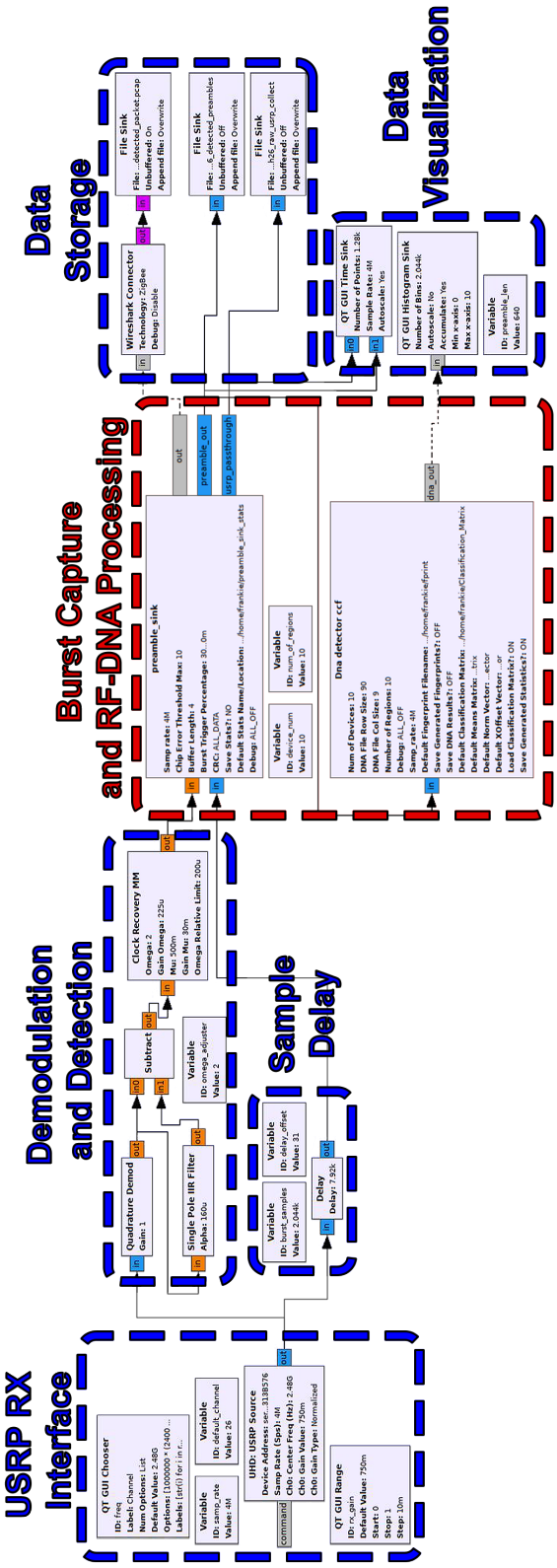


Figure 3.5. Complete GNU Radio Companion RF-DNA Air Monitor Flow Graph

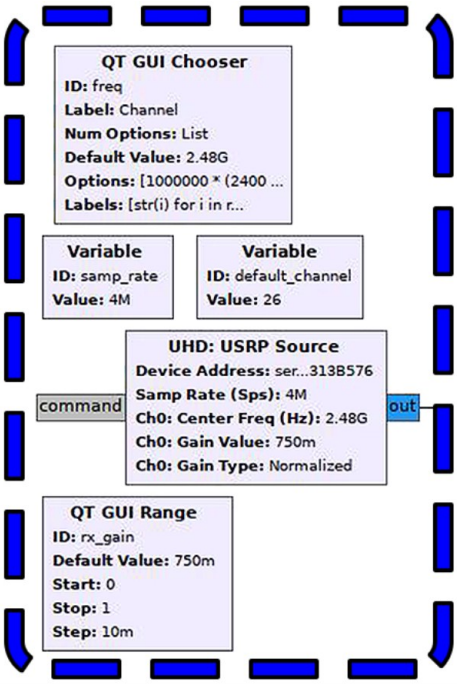


Figure 3.6. USRP RX Interface Blocks

was set to a sample rate $R_{\text{Samp}} = 4.0$ MSamp/sec as a global variable with *samp_rate*. The *QT Graphical User Interface (GUI) Chooser freq* block provides users the ability to change the B205mini-i's center frequency f_C at runtime with a drop-down list of channels between $f_{Ch} = 11$ to 26 based on (2.1). Each channel between 2405.0 MHz $\leq W_{rng} \leq$ 2480.0 MHz was evaluated to ensure that the air monitor operated as intended, but channel $f_{Ch} = 26$ ($f_C = 2.48$ GHz) was the default runtime value passed to *freq* throughout this research. The *QT GUI Range block* provides a slider for the users to modify the normalized receive gain variable *rx_gain*. The *rx_gain* is set to a default normalized receiver gain value $G_{RX_{Norm}} = 0.75$ thats adjustable in 0.1 increments between $G_{RX_{Norm}} = 0.0$ to 1.0 during runtime. The *UHD: USRP_Source* block controls and interacts directly with the B205mini-i. The the serial number of the target device must be entered for the device to start. The B205mini-i in this research was configured using the *freq*, *samp_rate*, and *rx_gain* block values on a single RX channel with a normalized gain. The maximum output buffer size of the *UHD: USRP_Source* block was increased

to an arbitrary value of 10 GSamp in the blocks *Advanced* tab to acquire as much buffer space GNU Radio would allow. This was done to help reduce the buffer overflows raw binary RX data, statistical files, fingerprint data, and `libpcap` files were simultaneously stored during collection trials.

3.1.2.2 Demodulation and Detection.

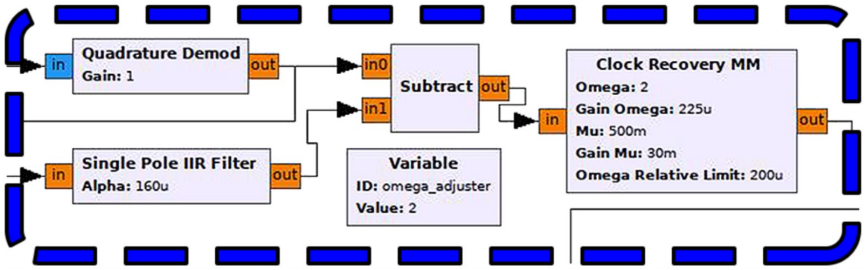


Figure 3.7. Demodulation and Detection Blocks

The demodulation and detection blocks on Figure 3.7 are composed from the *IEEE 802.15.4 O-QPSK PHY* transceiver RX blocks source code from Figure 3.4 and the *omega_adjuster* variable block. The detailed theoretical calculations behind the *Quadrature Demod*, *Single-Pole IIR Filter*, and *Clock Recovery MM* blocks are outside of the scope of this research. The derivations for these block's initial values can be found on GNU Radio's Manual and C++ API website [22]. Functionally, the complex baseband samples received from the *UHD: USRP_Source* block are demodulated by the *Quadrature Demod* block as an Minimum Shift Keying (MSK) transmission. Before the demodulated signal is passed to the *Clock Recovery MM* block to detect RX IEEE 802.15.4 chips, the high frequency components are removed from the collected samples with the *Single Pole infinite impulse response (IIR) Filter* block. The *Clock Recovery MM* block is a Mueller and Müller (M&M) discrete-time error-tracking synchronizer that outputs samples at a rate $R_{MM} = 1$ Sample/Recovered Symbol. According to GNURadio's website [22], the *Clock Recovery MM* inputs:

- *Omega* - Sets an initial estimate of samples per symbol.
- *Gain Omega* - Establishes the feedback gain setting for the *Omega* update loop.
- *Mu* - Sets an initial estimate of phase of sample.
- *Gain Mu* - Establishes the feedback gain setting for *Mu* update loop.
- *Omega Relative Limit* - Sets the maximum relative limit

The *Clock Recovery MM* block *Omega* requires adjustment if the sampling rate deviates from $R_{\text{Samp}} = 4$ MSamp/sec. The *omega_adjuster* block dynamically adjusts *Omega* using the IEEE 802.15.4 chip period $T_{\text{Chip}} = 0.5$ μsec/Chip and sampling rate R_{Samp} as

$$\omega = T_{\text{Chip}} \times R_{Samp}, \tag{3.1}$$

sets *Omega* to $\omega = 2$ samples between each chip as displayed on Figure 3.8. All other values were unchanged from the original *IEEE 802.15.4 O-QPSK PHY* transceiver block design.

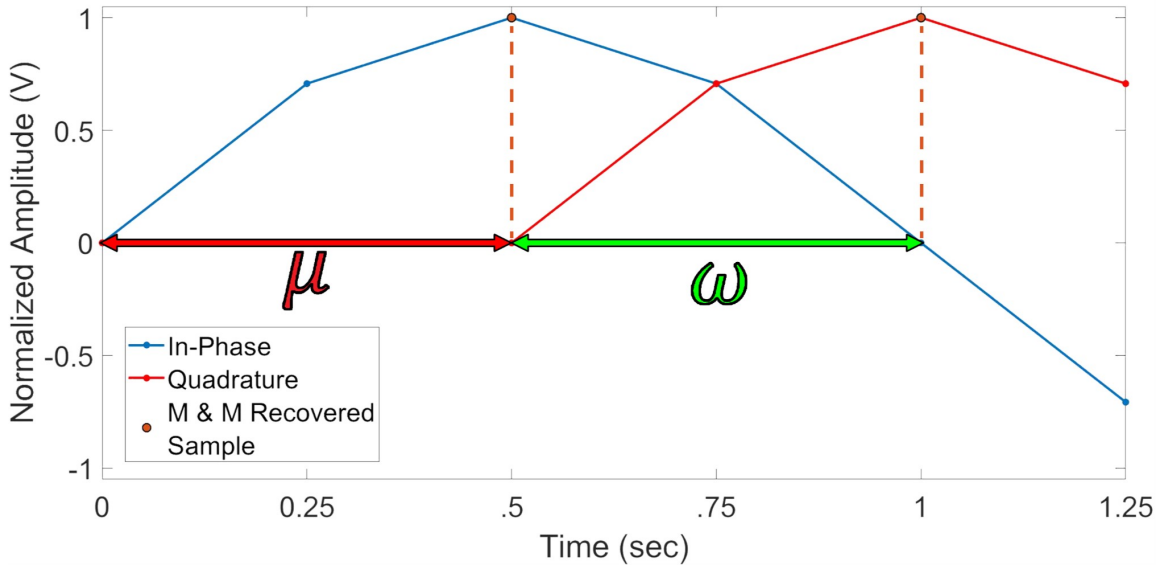


Figure 3.8. GNU Radio Clock Recovery M&M Illustration

3.1.2.3 Sample Delay.

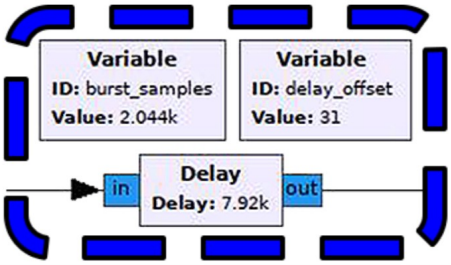


Figure 3.9. Sample Delay Blocks

The complex samples from the *UHD: USRP_Source* block were arriving at the *Packet Sink* block before the detected IEEE 802.15.4 chips could be used to properly capture an SHR sample sequence. The *Delay* block illustrated on Figure 3.9 was added to time shift captured samples by inserting a user specified number of zeroes in front of the received complex sample stream. The size of the delay N_{Delay} was controlled by the *burst_samples* and *delay_offset* variable blocks as

$$N_{\text{Delay}} = \lfloor \left(\frac{(burst\_samples \times delay\_offset)}{8} \right) \rfloor, \tag{3.2}$$

where *burst_samples* is $N_{\text{Samp}} = 2{,}044$ and *delay_offset* is $N_{\text{Mult}} = 31$. The number of samples N_{Samp} assigned to *burst_samp* was set to match the number of samples the *Packet Sink* block was designed to consume each function call. The *delay_offset* multiplier delays the received complex samples approximately 255 samples at a time contingent on *burst_samp* and (3.2). With a *delay_offset* $N_{\text{Mult}} = 32$ and a sampling period $T_{\text{Samp}} = 250$ nsec based on

$$T_{\text{Samp}} = \frac{1}{R_{Samp}} \tag{3.3}$$

a delay of $N_{Delay} = 7{,}665$ empty samples ($T_{Delay} = 1{,}916.25$ μsec) ensured the *UHD: USRP_Source* data stream was received within an appropriate time. The delay multiplier N_{Mult} could vary between different collection configurations, but N_{Mult} was ad-

justed to 32 after inspecting the delay period between several captured SHR samples in MATLAB against IEEE 802.15.4 samples from the B205mini-i.

3.1.2.4 Burst Capture and RF-DNA Processing.

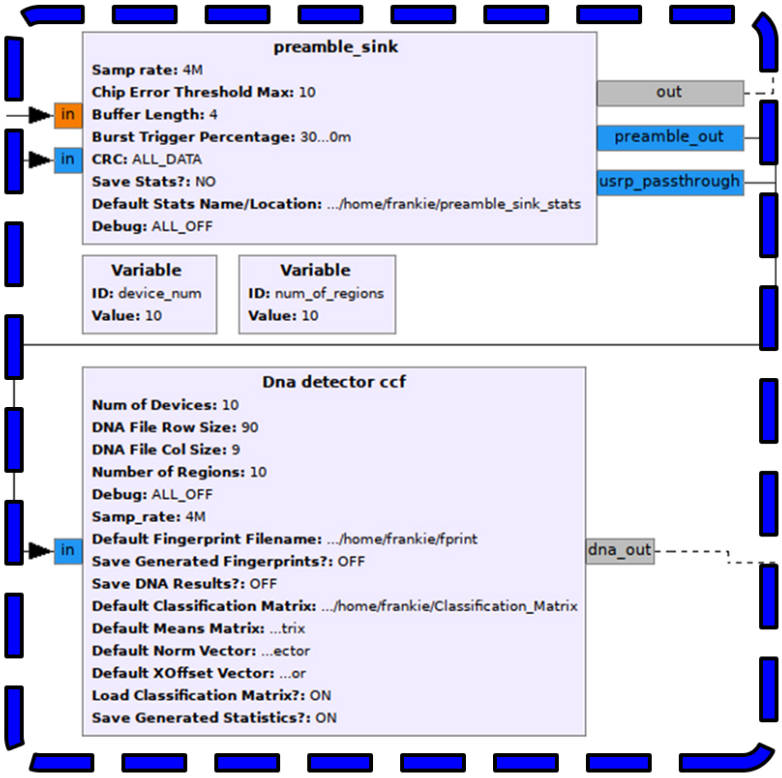


Figure 3.10. Burst Capture and RF-DNA Processing Blocks

The original *Packet Sink* block is a DSSS demodulation state machine that creates and forwards IEEE 802.15.4 PSDU packets to an asynchronous message output. The *preamble_sink* block added an *in* input to receive complex data; an *usrp_passthrough* that forwards received complex data used to detect IEEE 802.15.4 SHR bursts; and several optional data processing inputs. The following options added include:

- *Samp rate* - Automatically adjusts the numbers of samples to capture during burst detection by the input sample rate. *Samp rate* was set $R_{\text{Samp}} = 4\text{MSamp/s}$ by the global *samp_rate* block.

- *Chip Error Threshold Max* - Determines the acceptable number of chip mismatch errors during DSSS demodulation before the state machine is reset. *Chip Error Threshold Max* was set to 10-chips.

- *Buffer Length* - Establishes how many previous bursts are stored within a First-In-First-Out (FIFO) buffer queue. The *Buffer Length* was set to 4-bursts.

- *Burst Trigger Percentage* - Set's the burst detection's trigger threshold as a percentage of a detected and normalized IEEE 802.15.4 burst. *Burst Trigger Percentage* was set to 0.3.

- *Cyclic Redundancy Check (CRC)* - Enables the user to accept any detected burst or just CRC-16 verified bursts (CRC-16 algorithm extracted from *mac* class in the *gr-ieee802-15-4* module). *CRC* was configured to accept any detected bursts.

- *Save Stats* - Enables the user to store statistical information in a text file each time the air-monitor is activated. *Save Stats?* was enabled.

- *Default Stats Name/Location* - Prompts user for the name and location of the statistical file. A timestamp is added to the filename and stored as a text file. *Default Stats Name/Location* was set to store in the root directory formatted with the device identifier, channel number, and block name as *"Emitter##_Ch26_preamble_sink_stats"*.

- *Debug* - Provides different levels of diagnostic data displayed on the runtime console. *CHIP_ON* displays chip processing information, *PACKET_ON* displays packet information, and *USRP_ON* displays burst information. Any combination of the three options can be enabled. *Debug* was set to *ALL_OFF*.

The complex samples from the B205mini-i had to be captured whenever an SHR binary sequence was detected. Each burst within the *preamble_sink* block was de-

signed to consist of 2,044 complex float samples from the *Delay* block along with 1,022 float samples from the *Clock Recovery MM* block. Both sample streams were not perfectly in sync and the number of received samples occasionally varied, so a buffer of previously collected samples had to be created. A snapshot of the buffered and current B205mini-i data were stored together in a separate buffer when a IEEE 802.15.14 SHR sequence was detected. Once the IEEE 802.15.4 packet is completely filled in the *STATE_HAVE_HEADER* state, the IEEE 802.15.4 SHR waveform stored within the temporary buffer created inside *STATE_SYNC_SEARCH* is detected. This was done by modifying *Packet Sink*'s state machine where:

- *STATE_SYNC_SEARCH* - Continually searches for an a valid SHR sequence until one is found. The current waveform samples are appended to the end of the burst buffer before the entire sample sequence is stored in a temporary buffer for burst detection and the current state is changed to *STATE_HAVE_SYNC*.

- *STATE_HAVE_SYNC* - Searches the PHY Header (PHR) for the packet length and changes the state to *STATE_HAVE_HEADER* if the packet length is valid.

- *STATE_HAVE_HEADER* - Processes and transmits a complete IEEE 802.15.4 PSDU packet. Complex IEEE 801.15.4 SHR waveform samples are extracted during burst detection then loaded to the output signal buffer. The state is reset back to *STATE_SYNC_SEARCH*. Section 3.2 will provide more details on the burst detection process.

The state machine's PSDU packet buffers are cleared and *preamble_sink*'s states are reset any time an invalid DSSS demodulated symbol is detected as shown on Figure 3.11.

The *Dna detector ccf* block performs RF-DNA fingerprinting and device discrimination in NRT on each received SHR burst. The *Dna detector ccf* block settings have

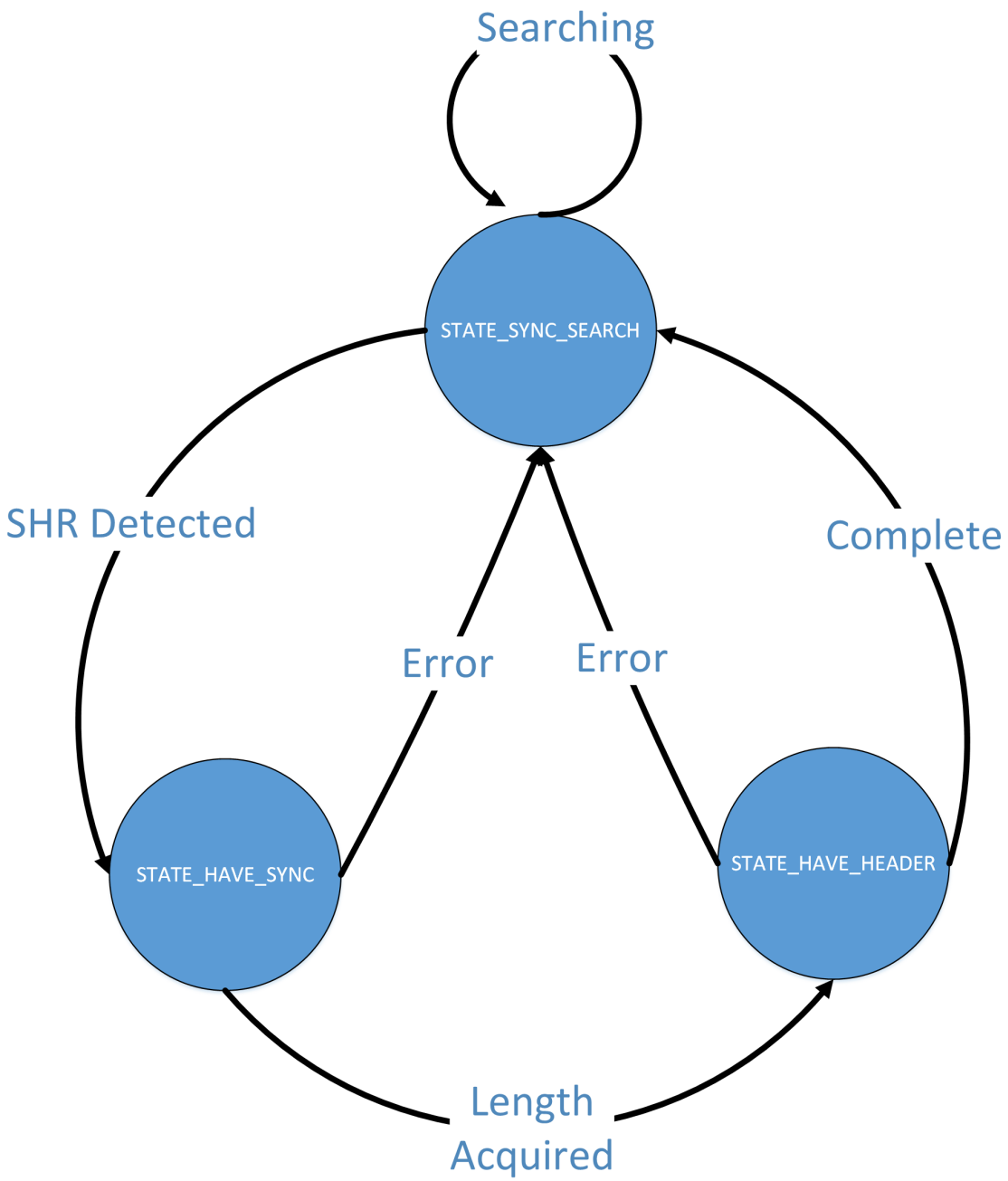


Figure 3.11. Finite State Machine Diagram for *preamble_sink*

different options for the collection and operational trials. The collection trial generated and stored fingerprints, and complex samples to a file. The operational trial generated fingerprints and performs Multiple Discriminant Analysis (MDA) classification in NRT. The data utilized and generated by the *Dna detector ccf* block was located in the root

directory. The *Dna detector ccf*'s block options settings include:

- *Num of Devices* - Number of devices set by the *device_num* block. The *Num of Devices* was set to 10 devices by the *device_num* block.
- *DNA File Row Size* - Row length of the MDA projection matrix $\mathbf{W}$ based on (2.17). *DNA File Row Size* was set to 90.
- *DNA File Col Size* - Column length of the MDA projection matrix $\mathbf{W}$ set by (*device_num* block - 1). *DNA File Col Size* was set to 9 by the *device_num* block.
- *Number of Regions* - Number of regions used for fingerprinting analysis. The *num_of_regions* block was set to 10 regions.
- *Debug* - Provides different levels of diagnostic data displayed on the runtime console like preamble_sink's *Debug* option. *Debug* was set to *ALL_Off*.
- *Samp_rate* - Automatically adjusts the numbers of samples to process during RF-DNA fingerprinting. *Samp_rate* was set $R_{\text{Samp}} = 4\text{MSamp/s}$ by the global *samp_rate* block.
- *Default Fingerprint Filename* - Prompts user for the name and location to save the collected fingerprints as a binary data file. The *Default Fingerprint Filename* was set to set to *"Emitter##_Ch26_fprint"*.
- *Save Generated Fingerprints* - Enables the user to store RF-DNA fingerprints $\mathbf{F}_{\text{TD}}$ as binary data on a file in NRT. *Save Generated Fingerprints* was enabled during the collection performance trials and disabled for the operational performance trials.
- *Save DNA Results* - Enables the user to store projection results $\widehat{\mathbf{f}}$ based on (2.23) as a binary data on a file in NRT. *Save DNA Results* was disabled.

- *Default Classification Matrix* - Prompts user for the location of the MATLAB generated MDA/ML projection matrix $\mathbf{W}$ file.

- *Default Means Matrix* - Prompts user for the location of the MATLAB generated means matrix $\mathbf{W}_{\mu}$ file.

- *Default Norm Vector* - Prompts user for the location of the MATLAB generated gain normalization vector $\mathbf{F}_{\text{TD Norm}}$ file.

- *Default XOffset Vector* - Prompts user for the location of the MATLAB generated x-offset vector $\mathbf{F}_{\text{TD XOffset}}$ file.

- *Load Classification Matrix* - Enables the user to load the MATLAB generated $\mathbf{W}$, $\mathbf{W}_{\mu}$, $\mathbf{F}_{\text{TD Norm}}$, and $\mathbf{F}_{\text{TD XOffset}}$ files for NRT device discrimination. *Load Classification Matrix* was disabled during the collection performance trials and disabled for the operational performance trials.

- *Save Generated Statistics* - Enables the user to store two separate timestamped statistical text files. *Save Generated Statistics* was enabled. The *"Emitter##_Ch26_fprint_matrix_mult"* generated file keeps track of the NRT generated fingerprints $\mathbf{F}_{\text{TD}}$ and detailed discrimination results. The *"Emitter##_Ch26_fprint_matrix_mult"* file keeps track of statistical information on each device.

Section 3.3.2 provides more detailed information on the NRT fingerprinting process and Section 3.4 provides more information about the MDA/ML support files necessary for NRT device discrimination.

The *Dna detector ccf* block is a state machine as displayed on Figure 3.12 where:

- *SEARCHING* - The *preamble_sink* block generates empty complex floats from the *preamble output* port until an IEEE 802.15.4 SHR is detected. The current state

is changed to a *DETECTED* state once a sample received from the *preamble_sink* block exceeds a threshold value of 1.0e-38.

- *DETECTED* - Changes the state to *FINGERPRINT* after a sample buffer is filled. The *Samp_rate* input determines how many samples are captured within the buffer.

- *FINGERPRINT* - A fingerprint is created from the buffered SHR samples. MDA analysis is performed on the collected fingerprint using trained data and/or stores fingerprints to create trained data. MDA results are passed to the asynchronous message output and the state is reset back to *SEARCHING*.

3.1.2.5 Data Visualization.

Data was displayed using *QT GUI Histogram Sink* and *QT GUI Time Sink* blocks as shown on Figure 3.13. The *QT Histogram Sink* block is notified by the *Dna detector ccf* block which device was identified. The *device_num* variable block sets the *QT GUI Histogram Sink*'s X-axis. The *QT GUI Time Sink* block displays both the B205mini-i's passed through collections and the detected IEEE 802.15.4 SHR bursts from the *preamble_sink* block. The *preamble_len* and *samp_rate* blocks values are used to set the *QT GUI Time Sink's Number of Points* and *Sample Rate* inputs. The *preamble_len* block calculates the IEEE 802.15.4 SHR sample length as

$$N_{\text{SHR Samples}} = N_{\text{SHR Chips}} \times T_{\text{Chip}} \times R_{\text{Samp}}, \tag{3.4}$$

where *preamble_len* $N_{\text{SHR Samples}} = 640$ samples ($T_{\text{SHR}} = 160$ μsec) when the sampling rate $R_{\text{Samp}} = 4$ MSamp/sec, the chip period $T_{\text{Chip}} = 0.5$ μsec/Chip, and $N_{\text{SHR Chips}} = 320$ chips. The RF-DNA air-monitor GUI is composed of the *QT GUI Chooser freq*, *QT GUI*

detector ccf State Diagram.png detector ccf State Diagram.png

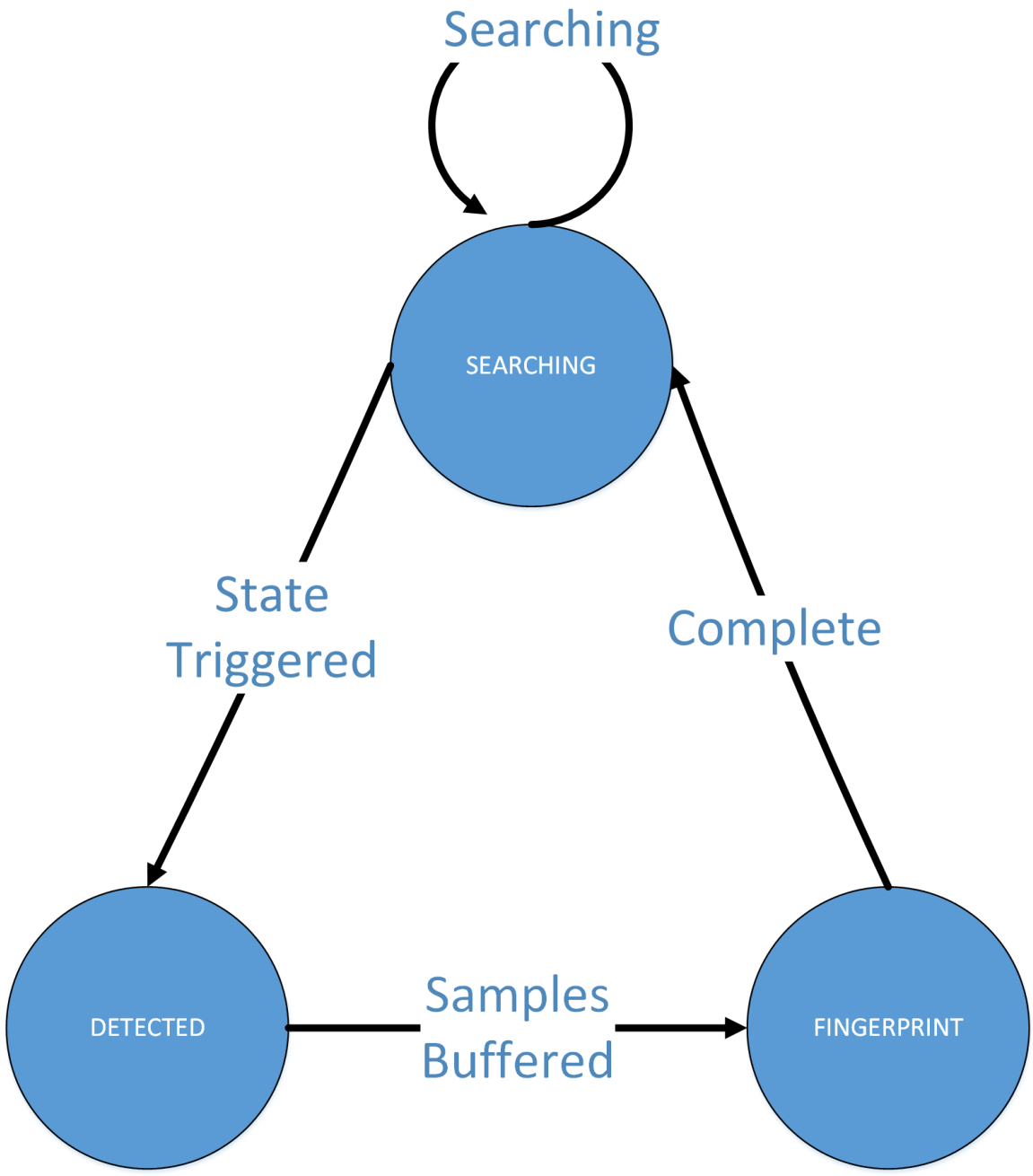


Figure 3.12. ***Dna detector ccf*** **Block State Diagram**

Range rx_gain,QT GUI Time Sink, and *QT GUI Histogram Sink* blocks as demonstrated on Figure 3.14.

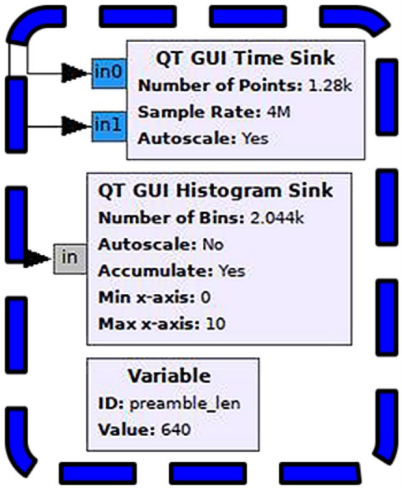


Figure 3.13. Data Visualization Blocks

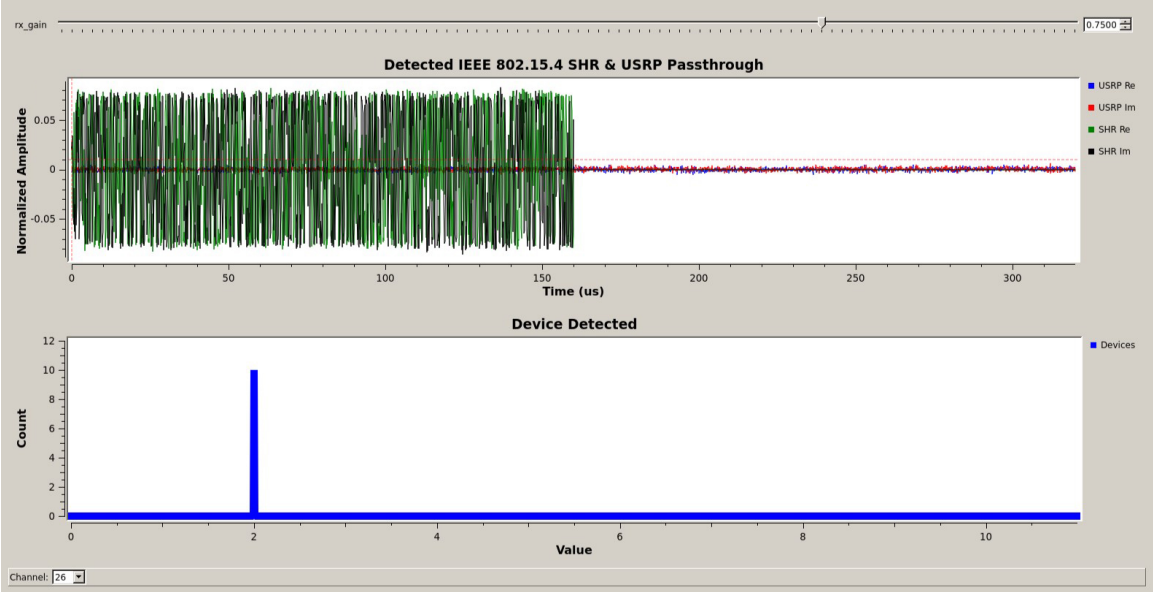


Figure 3.14. Air Monitor Operational GUI

3.1.2.6 Data Storage.

The *File Sink* blocks on Figure 3.15 stored binary complex data received from *preamble_sink* and binary byte data from the *Wireshark Connector* block. All of the collected data was set to store in the root directory. The complex data *File Sink* blocks were only enabled when fingerprints were being stored for off-line analysis. Each filename contained the device, channel number, and source as a complex float binary file as

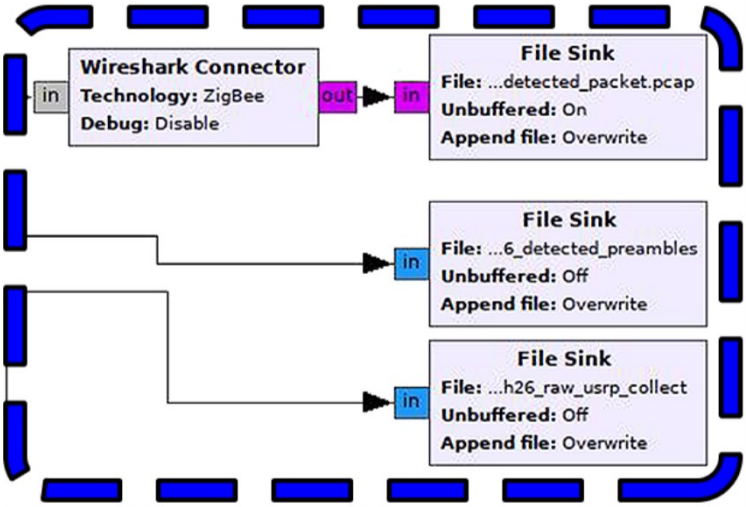


Figure 3.15. Data Storage Blocks

"Emitter##_Ch26_detected_preambles" and *"Emitter##_Ch26_raw_usrp_collect"*. Similarly, each IEEE 802.15.4 PSDU packet the *Wireshark Connector* block was received from the *preamble_sink* block were converted into a `libpcap` file. The `libpcap` files followed the same naming convention where the device and channel collected on were stored as *"Emitter##_Ch26_detected_packet.pcap"*.

3.2 Burst Detection

As mentioned in Section 3.1.2.4, each burst is captured and detected within the *preamble_sink* block. Burst detection begins once an IEEE 802.15.4 PSDU packet is fully processed within the the *STATE_SYNC_SEARCH*. The detection process is initiated by acquiring the largest instantaneous amplitude ($\mathbf{a}$) within the temporary buffer $\mathbf{x}[n]$ containing the captured samples from the *STATE_SYNC_SEARCH* state as

$$C_{\text{Max}} = \text{Max}(\mathbf{a}[n]), \qquad n = \{0,1,2,...,N-1\} \tag{3.5}$$

to create a normalized instantaneous amplitude $\mathbf{a}[n]_{\text{Norm}}$ by

$$\mathbf{a}[n]_{\text{Norm}} = \frac{\mathbf{a}[n]}{C_{\text{Norm}}}, \qquad n = \{0, 1, 2, ..., N-1\}. \tag{3.6}$$

The burst detection threshold $t_D = 0.3$ established by *Burst Trigger Percentage* in the *preamble_sink* block was used detect the index point N_{Index} where

Algorithm 1 Threshold Detection

```
function BURST TRIGGER(a[n]_Norm, t_D, N_Index)
    n = 0
    N = length(a[n]_Norm)
    while n < N do
        if a[n]_Norm ≥ t_D then
            N_Index = n
            break
        end if
        n = n + 1
    end while
    return N_Index
end function
```

N_{Index} and the number of samples within an IEEE 802.15.4 SHR N_{SHR} were used to determine if $\mathbf{x}[n]$ contains enough samples to properly create a detected SHR sequence $\mathbf{x}[n]_{\text{Detected}}$ by Algorithm 2.

The temporary buffer $\mathbf{x}[n]$ containing the detected burst is composed of approximately $N \approx 10{,}220$ samples when the *Buffer Length* is configured to store 4 bursts and 2,044 samples from the most recent burst. At $R_{\text{Samp}} = 4$ MSamp/sec, the burst detector will search for $N_{\text{SHR}} = 640$ samples within $\mathbf{x}[n]$. Figure 3.16 contains a complete normalized IEEE 802.15.4 burst triggered at $t_D = 0.3$ and the detected SHR burst.

The purpose of normalizing the IEEE 802.15.4 SHR burst is to establish a starting point for burst detection. The unnormalized complex IEEE 802.15.4 SHR samples rendered on Figure 3.17 will be fingerprinted in the *Dna detector ccf* block.

Algorithm 2 Burst Detection

function BURST DETECTION($\mathbf{x}[n]$, N_{Index}, N_{SHR}, $\mathbf{x}[n]_{\text{Detected}}$)
  $n = 0$
  $N = \text{length}(\mathbf{x}[n])$
  if $(N_{\text{Index}} + N_{\text{SHR}} + 1) > N$ **then**
    while $n < N$ **do**
      $\mathbf{x}[n] = 0$
      $n = n + 1$
    end while
  else if $(N_{\text{Index}} + N_{\text{SHR}} + 1) \leq N$ **then**
    $n = N_{\text{Index}}$
    while $n < (N_{\text{Index}} + N_{\text{SHR}} + 1)$ **do**
      $\mathbf{x}[n]_{\text{Detected}} = \mathbf{x}[n]$
      $n = n + 1$
    end while
    while $n < N$ **do**
      $\mathbf{x}[n]_{\text{Detected}} = 0$
      $n = n + 1$
    end while
  end if
  return $\mathbf{x}[n]_{\text{Detected}}$
end function

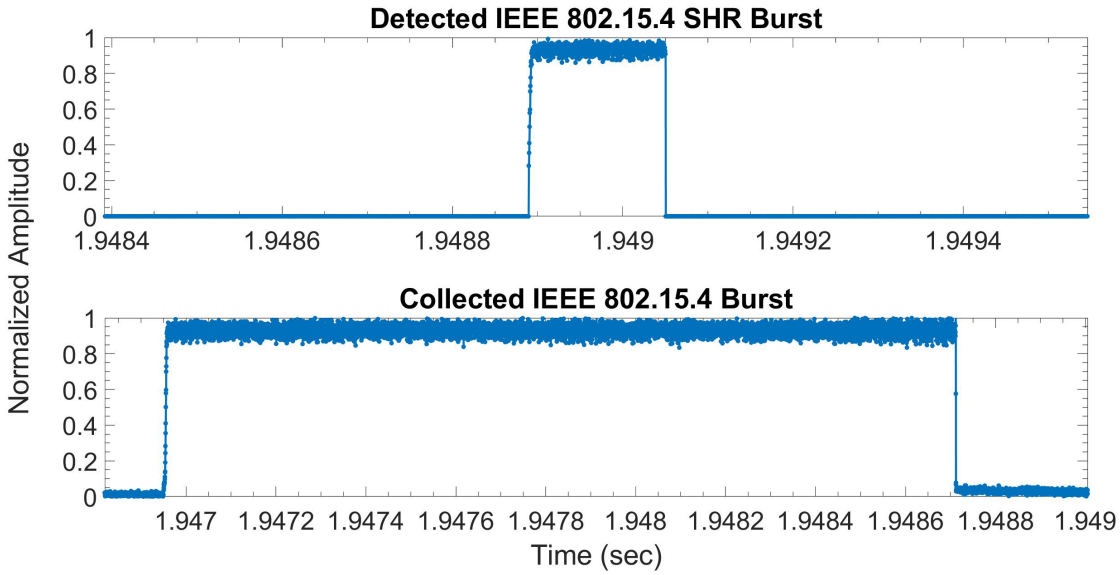


Figure 3.16. Normalized IEEE 802.15.4 Packet and SHR Bursts from Device 10

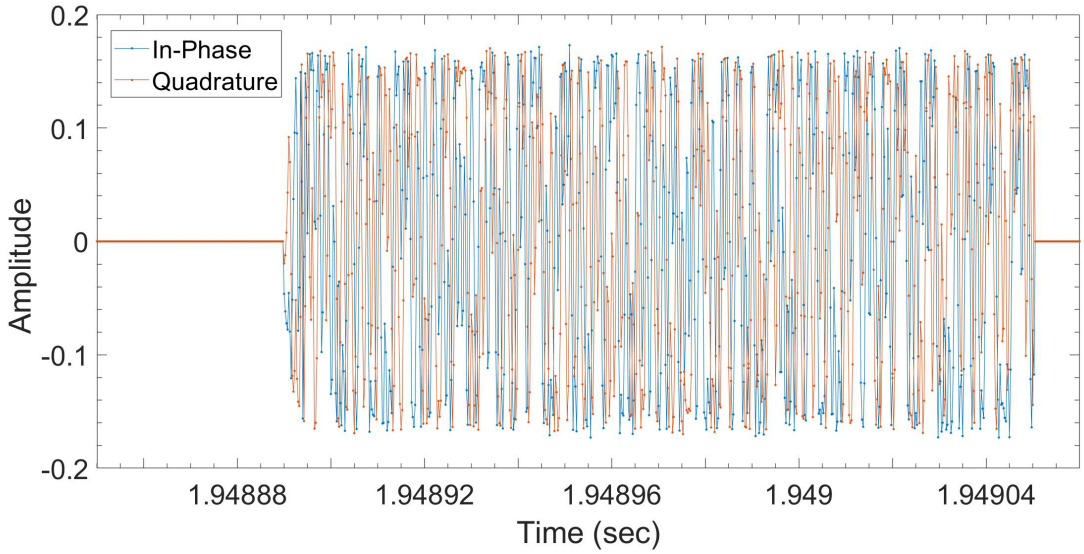


Figure 3.17. Detected IEEE 802.15.4 SHR Burst from Device 10

3.3 Fingerprint Generation

Full-dimensional Time Domain (TD) fingerprints $\mathbf{F}_{\text{TD}}$ generated in this research with MATLAB and the *Dna detector ccf* block were $N_{\text{TD}} = 90$ samples long from each captured IEEE 802.15.4 SHR waveform samples. Each full-dimensional TD fingerprint $\mathbf{F}_{\text{TD}}$ was comprised of $N_R = 10$ Region(s) of Interest (ROI), $N_F = 3$ features per ROI, and $N_M = 3$ statistical metrics per feature as listed in Section 2.4 such that

$$\mathbf{F}_{\text{TD}} = \left[\mathbf{F}_1^{\text{a}} \vdots \mathbf{F}_1^{\phi} \vdots \mathbf{F}_1^{\text{f}} \vdots \ldots \vdots \mathbf{F}_{10}^{\text{a}} \vdots \mathbf{F}_{10}^{\phi} \vdots \mathbf{F}_{10}^{\text{f}}\right]_{[1\times3\times3\times10]=[1\times90]}. \tag{3.7}$$

The MATLAB generated fingerprints were used specifically to create an estimative $\text{MDA/ML}_{\text{Est}}$ model simulating an environment with a variable Signal-to-Noise Ratio (SNR) to compare against the air monitor's fingerprint trained $\text{MDA/ML}_{\text{Air}}$ model.

The average signal power S and average noise power N were used to calculate the SNR as

$$\text{SNR} = 10\log_{10}\left(\frac{S}{N}\right), \tag{3.8}$$

where the average power of a complex signal $\mathbf{x}[n]$ is calculated with it's complex conjugate $\mathbf{x}^*[n]$ is given by

$$X = \frac{1}{N}\sum_{n=0}^{N-1}\mathbf{x}[n]\mathbf{x}^*[n]. \tag{3.9}$$

The captured IEEE 802.15.4 signal $\mathbf{s}[m]_c$ is composed from the collected transmitted signal $\mathbf{s}[m]$ and collected background noise $\mathbf{n}[m]_b$,

$$\mathbf{s}[m]_c = \mathbf{s}[m] + \mathbf{n}[m]_b\,, \quad m = \{0,1,2,...,M-1\}, \tag{3.10}$$

such that the captured signal $\mathbf{s}[m]_c$ average power S_c, collected transmitted signal $\mathbf{s}[m]$ average power S, and collected background noise $\mathbf{n}[m]_b$ average power N_b is calculated as

$$\begin{aligned} S_c &= S + N_b, \\ S_c &= \frac{1}{M}\sum_{m=0}^{M-1}\mathbf{s}[m]_c\,\mathbf{s}^*[m]_c\,, \\ S &= \frac{1}{M}\sum_{m=0}^{M-1}\mathbf{s}[m]\mathbf{s}^*[m], \\ N_b &= \frac{1}{M}\sum_{m=0}^{M-1}\mathbf{n}[m]_b\,\mathbf{n}^*[m]_b\,, \end{aligned} \tag{3.11}$$

where the collected background noise $\mathbf{n}_b[m]$ was measured where there were no signals present. The MATLAB modeled fingerprints added scaled Additive White Gaussian Noise (AWGN) noise $\mathbf{n}_{\mathrm{AWGN}[m]}$ from SNR = 0 to 40 dB in 5dB increments. Sections 3.3.1 and 3.3.2 will explain how each set of fingerprints were created.

3.3.1 MATLAB Fingerprint Generation.

The data originally collected was created from a Pseudo Random Noise Generated (PRNG) sequence and stored in a text file. The text file was converted to a libpcap

file using *zbconvert* so that IEEE 802.15.4 bursts could be generated using *zbreplay*. Each RZUSBstick transmitted $N_{\text{Bursts}} = 12{,}000$ bursts on channel $f_{Ch} = 26$ ($f_C = 2.48$ GHz) at $T_{\text{Burst}} = 50$ msec intervals. The RZUSBstick transmitted inside a Ramsey test enclosure, and the signal was collected at a sample rate of $R_{\text{Samp}} = 10$ MSamp/sec. The burst detection computed moving average of the energy of the collected signal, and determined the presence of a burst once the moving average exceeded a specified threshold.

The data used to generate the MATLAB fingerprints was collected for each RZUSBstick device before development on the air monitor began. The air monitor captured data at a sample rate of $R_{\text{Samp}} = 4$ MSamp/sec per the design of the original *IEEE 802.15.4 O-QPSK PHY* transceiver block. The sample rate was kept at $R_{\text{Samp}} = 4$ MSamp/sec to ensure that the air monitor's original receive functionality did not deviate from the intended design. The previously collected data had to be resampled from $R_{\text{Samp}} = 10$ MSamp/sec to $R_{\text{Samp}} = 4$ MSamp/sec before the MATLAB fingerprints could be modeled with AWGN.

The first step to properly resample the off-line processed data was to up-sample the collected signal $\mathbf{x}[n]$ by a factor of 2 for a resulting sampling rate of $R_{\text{Samp}} = 20$ MSamp/sec by interpolating zeroes. Figure 3.18 is a normalized burst from the collected signal $\mathbf{x}[n]$ at $R_{\text{Samp}} = 10$ MSamp/sec and Figure 3.19 is the up-sampled signal $\mathbf{x}[n]_{\text{Up}}$ at $R_{\text{Samp}} = 20$ MSamp/sec.

Then the up-sampled signal $\mathbf{x}[n]_{\text{Up}}$ is filtered with a 10-order low pass filter to mitigate the artifacts introduced by the up-sampling process. The upsampled-filtered signal $\mathbf{x}[n]_{\text{Filt}}$ represented on Figure 3.20 is finally down-sampled by a factor of 5 for a resulting sample rate of $R_{\text{Samp}} = 4$ MSamp/sec as shown on Figure 3.21

After the collected signal is re-sampled to $R_{\text{Samp}} = 4$ MSamp/sec, independent AWGN zero-mean, like-filtered noise samples $\mathbf{n}[m]_{\text{AWGN}}$ was added to the resampled

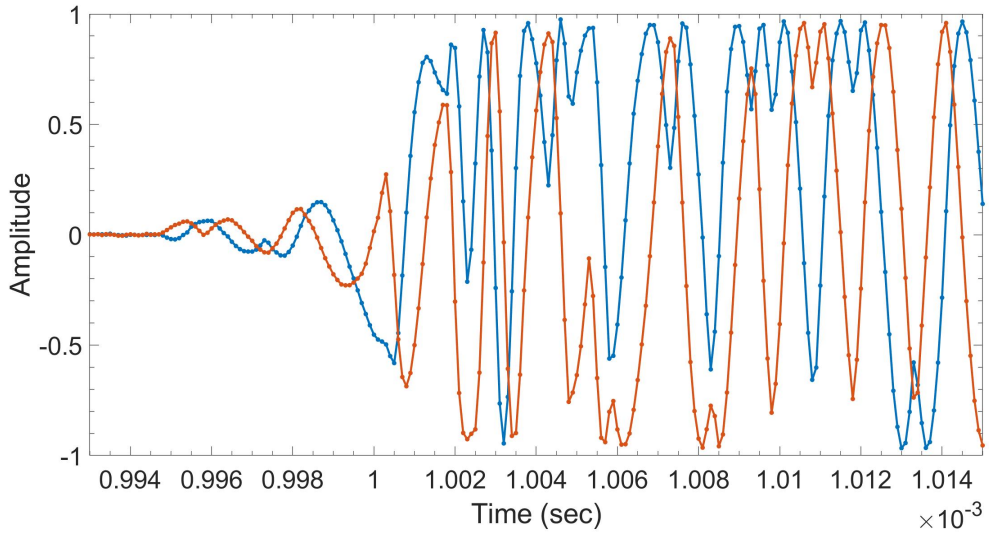


Figure 3.18. Normalized Burst at $R_{\text{Samp}} = 10$ MSamp/sec from Device 10

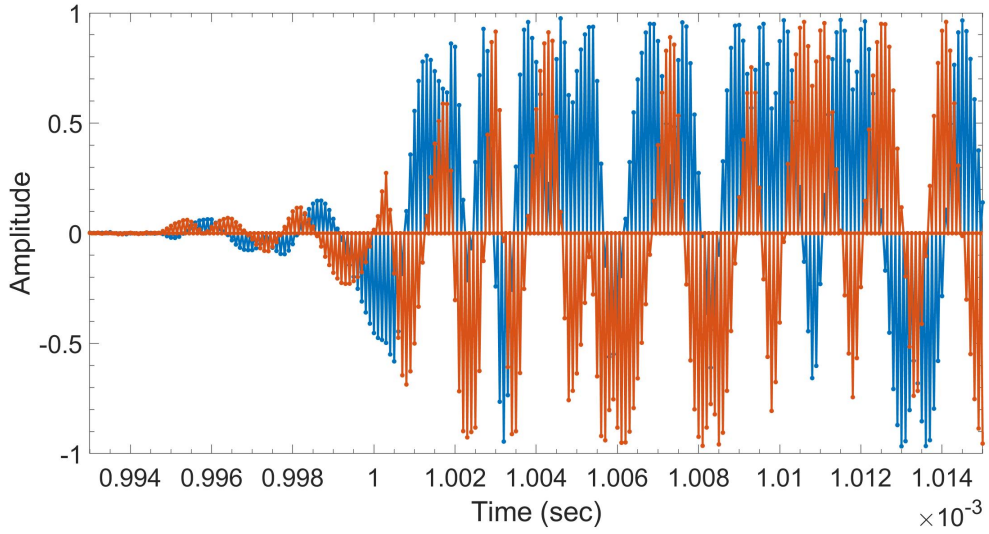


Figure 3.19. Normalized Burst at $R_{\text{Samp}} = 20$ MSamp/sec from Device 10

data $\mathbf{x}[m]_{\text{Resamp}}$ as

$$\mathbf{x}[m]_{\text{Model}} = \mathbf{x}[m]_{\text{Resamp}} + \mathbf{n}[m]_b + \mathbf{n}[m]_{\text{AWGN}}, \quad m = \{0,1,2,...,M-1\}, \tag{3.12}$$

where the average power of $\mathbf{n}[m]_{\text{AWGN}}$ is scaled to achieve an SNR = 0 to 40 dB [9].

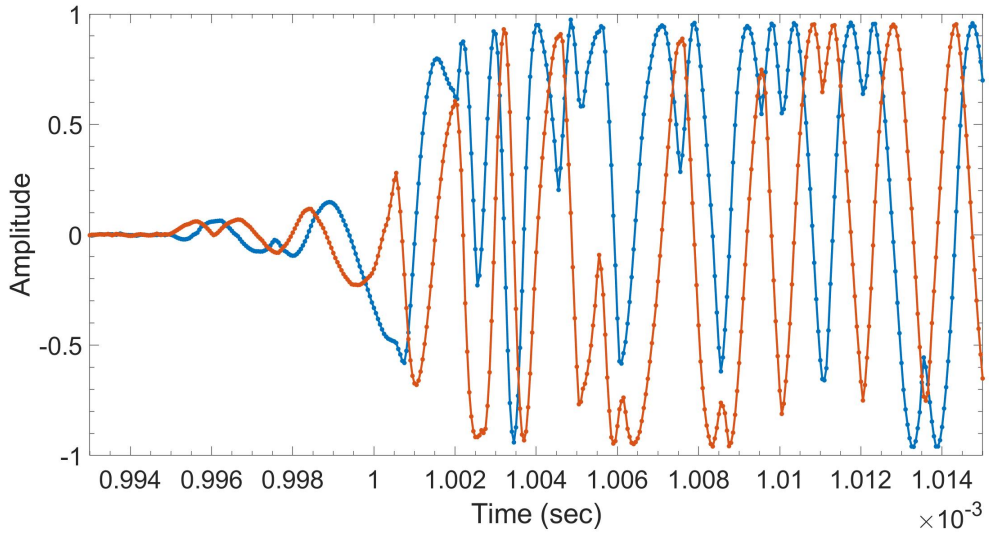


Figure 3.20. Filtered Normalized Burst at $R_{\text{Samp}} = 20$ MSamp/sec from Device 10

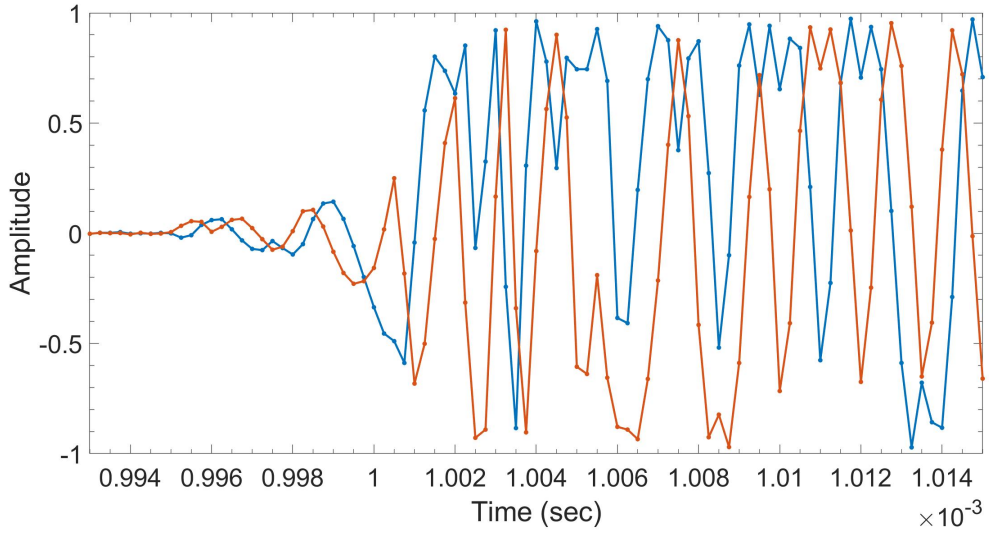


Figure 3.21. Normalized Burst at $R_{\text{Samp}} = 4$ MSamp/sec from Device 10

Each noise sample sequence $\mathbf{n}[m]_{\text{AWGN}}$ has an estimated average power of $N = 1$ dB that is power scaled by the downsampled signals average power X_{Resamp} and a desired SNR such that

$$A_{\text{AWGN}} = \sqrt{10^{\frac{-\text{SNR}_{\text{Desired}}}{10}} \times X_{\text{Rsamp}}}, \tag{3.13}$$

where A_{AWGN} is a noise scaling multiplier used to calculate the total average desired noise power N_{AWGN} as

$$N_{\text{AWGN}} = \frac{1}{M}\sum_{m=0}^{M-1} A_{\text{AWGN}}\mathbf{n}[m]_{\text{AWGN}}\, A_{\text{AWGN}}\mathbf{n}^*[m]_{\text{AWGN}}. \tag{3.14}$$

The resampled collection $\mathbf{x}[n]_{\text{Resamp}}$ will add the total average desired noise power N_{AWGN} from an SNR = 0 to 40 dB in 5 dB increments into the SNR modeled samples $\mathbf{x}[n]_{\text{Model}}$ as

$$X_{\text{Model}} = X_{\text{Resamp}} + N_b + N_{\text{AWGN}}, \tag{3.15}$$

before each burst is fingerprinted. The SNR for each modeled sample collection $\mathbf{x}[n]_{\text{Model}}$ can be calculated by extending (3.8) using

$$\text{SNR} = 10\log_{10}\left(\frac{X_{\text{Model}}}{N_b + N_{\text{AWGN}}}\right). \tag{3.16}$$

3.3.2 GNU Radio Fingerprint Generation.

Each RZUSBstick was programmed to replay *control4-sample.pcap*, a `libpcap` containing ZigBee data from a Control4® appliance. The `libpcap` file transmitted $N_{\text{Bursts}} = 239$ bursts on channel $f_{Ch} = 26$ ($f_C = 2.48$ GHz) at $T_{\text{Burst}} = 10$ msec intervals between bursts. A bash script was created to consecutively replay the file 8-times with *zbreplay* to generate $N_{\text{Bursts}} = 1{,}912$ bursts on each device. More information will be provided on about the transmitted IEEE 802.15.4 data packets in Chapter IV. Figure 3.22 is one iteration of *control4-sample.pcap* on device 10.

The captured signals $\mathbf{x}[n]_c$ SNR was calculated using

$$\text{SNR} = 10\log_{10}\left(\frac{X_c - N_b}{N_b}\right) = 10\log_{10}\left(\frac{(X+N_b)-N_b}{N_b}\right) \approx 10\log_{10}\left(\frac{X}{N_b}\right) \tag{3.17}$$

where the average background noise power N_b is assumed to be captured within the

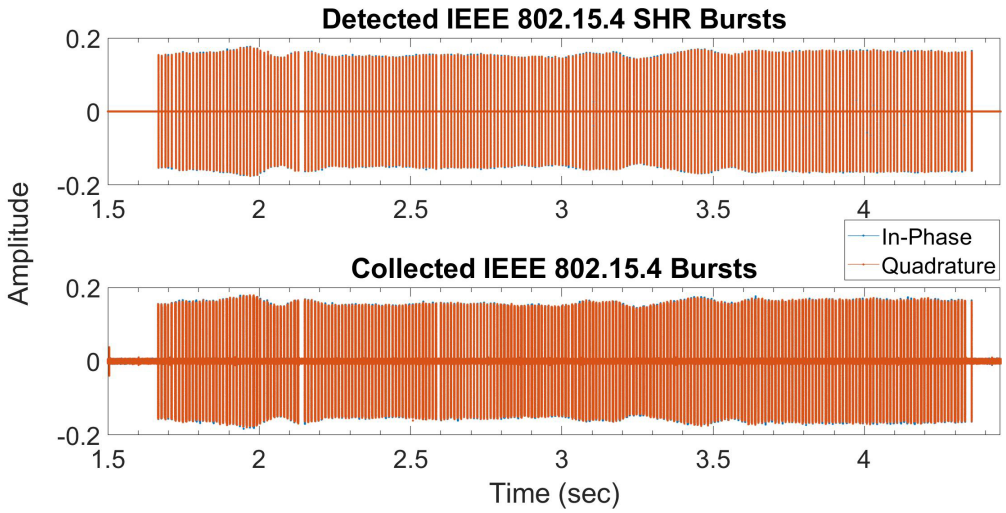


Figure 3.22. $N_{\text{Bursts}} = 239$ **Bursts from *control4-sample.pcap* on Device 10**

average captured signal's power X_c, so the measured background noise power N_b was removed from captured signals power X_c to get an approximate value for the average transmitted signals average power X. The captured signals $\mathbf{x}[n]_c$ SNR and fingerprint results will be covered in Chapter IV.

3.4 MDA/ML

The MATLAB and air monitor generated fingerprints for the $N_D = 10$ RZUSBsticks were used for MDA model development and Maximum Likelihood (ML) device classification. $N_F = 1{,}000$ fingerprints were taken for each set of SNR augmented bursts within MATLAB to generate an MDA/ML_{Est} model to formulate a comparative baseline for the air monitor at various SNR's. $N_F = 1{,}000$ fingerprints that were created by the air monitor were loaded into MATLAB to create an MDA/ML_{Air} model at the measured SNR. That air monitor's MDA_{Air} model was loaded into the *DNA detector ccf* block afterwards to discriminate devices in NRT.

MDA/ML processing was performed as described in Section 2.5. The process begins with each set of $N_F = 1{,}000$ fingerprints being separated into $N_{\text{Train}} = 500$ training

and $N_{\text{Test}} = 500$ testing fingerprint sets. Both N_{Train} and N_{Test} fingerprint sets were taken as interleaved subsets of the fingerprint set. The N_{Train} fingerprints were then fed into the MDA/ML classifiers where the model were created. A K-fold cross-validation processed was to used determine an ideal model for the given set with $K = 5$-folds. The developed models performance was measured by performing a "looks most like" assessment on each N_{Test} fingerprint set and assigning each set to the postulated device [9].

The air monitors MDA_{Air} model data consisted of a

- $\mathbf{W}_{[90\times9]}$ - MDA projection matrix
- $\mathbf{W}_{\mu[10\times9]}$ - Trained MDA class mean device projection matrix
- $\mathbf{F}_{\text{TD Norm}[1\times90]}$ - Fingerprint normalization gain vector
- $\mathbf{F}_{\text{TD XOffset}[1\times90]}$ -Fingerprint offset vector

where the $\mathbf{F}_{\text{TD Norm}}$ and $\mathbf{F}_{\text{TD XOffset}}$ must be applied to the *Dna detector ccf* block's $\mathbf{F}_{\text{NRT}}$ fingerprint because the MDA_{Air} model's values were normalized and offset in MATLAB to maintain a maximum dynamic range for the floating point representations. The offset and gain normalized fingerprint $\mathbf{F}_{\text{TD}}$ is represented by

$$\mathbf{F}_{\text{TD}} = (\mathbf{F}_{\text{NRT}} - \mathbf{F}_{\text{TD XOffset}}) \circ \mathbf{F}_{\text{TD Norm}}. \tag{3.18}$$

$\mathbf{F}_{\text{TD}}$ is then applied to a modified version of (2.23) so that

$$\widehat{\mathbf{f}} = \mathbf{F}_{\text{TD}}\mathbf{W} \tag{3.19}$$

where the resultant projection vector $\widehat{\mathbf{f}}$ computed the same results as (2.23), but the output dimensions were 1×9 instead of 9×1.

Finally, the resultant projection vector $\widehat{\mathbf{f}}$ is used to estimate the "most likely" device by calculating the minimum for Euclidean distance $\mathbf{d}_{\text{Min}}$ between the projection vector $\widehat{\mathbf{f}}$ and each vector row within $\mathbf{W}_{\mu}$ as

$$\begin{pmatrix} \left[\sqrt{\left(\mathbf{W}_{\mu_{1,1}}-\widehat{\mathbf{f}}_{1,1}\right)^2+\ldots+\left(\mathbf{W}_{\mu_{1,9}}-\widehat{\mathbf{f}}_{1,9}\right)^2}\right] \\ \vdots \\ \left[\sqrt{\left(\mathbf{W}_{\mu_{10,1}}-\widehat{\mathbf{f}}_{10,1}\right)^2+\ldots+\left(\mathbf{W}_{\mu_{10,9}}-\widehat{\mathbf{f}}_{10,9}\right)^2}\right] \end{pmatrix} = \begin{pmatrix} d_{1,1} \\ \vdots \\ d_{1,10} \end{pmatrix}, \tag{3.20}$$

$$\mathbf{d}_{\text{Min}} = \min\left(d_{1,m}\right) \quad \text{for } m = \{1,\ldots,10\},$$

where the row number of the Euclidean distance vector $\mathbf{d}$ with the minimum Euclidean distance $\mathbf{d}_{\text{Min}}$ corresponds to the "most likely" device. The results of discriminating between devices in NRT will be discussed in Chapter IV.

IV. Analysis of Results

This chapter provides the results for ZigBee device discrimination in Near Real-Time (NRT) with the GNU Radio air monitor, to include comparing predictive performance *Device Classification* estimations against live results using Radio Frequency-Distinct Native Attribute (RF-DNA) Fingerprints generated and collected in NRT. This chapter is organized as follows: Section 4.1 provides details on the GNU Radio air monitor NRT fingerprinting performance while simultaneously storing collection data. Section 4.2 provides details on the GNU Radio air monitor operational performance after Multiple Discriminant Analysis/Maximum Likelihood (MDA/ML) trained data has been loaded and data storage was disabled. This is followed by Section 4.3 where an estimative Additive White Gaussian Noise (AWGN) MATLAB and air monitor trained MDA/ML models will be created. Section 4.4 concludes Chapter IV by providing the device discrimination results of the GNU Radio air monitor.

4.1 GNU Radio Air Monitor Collection Performance Analysis

The air monitor's collection performance was assessed based on how well the Software-Defined Radio(s) (SDR) detected Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 bursts from each device; how well the *preamble_sink* block extracted IEEE 802.15.4 Synchronization Header (SHR) waveform samples from the detected bursts; and how well the *Dna detector ccf* block fingerprinted and discriminated devices from the extracted SHR samples from the *preamble_sink* block while simultaneously storing data. The air monitor had each complex file sink storing complex data

at

$$
\begin{aligned}
R_{\text{Complex}} &= R_{\text{Samp}} \times N_{\text{Complex Size}} \times N_{\text{Byte Size}}, \\
R_{\text{Complex}} &= (4\ \text{MSamp/sec})(8\ \text{B/Samp})(8\ \text{Bits/B}), \\
R_{\text{Complex}} &= (32\ \text{MB/sec})(8\ \text{Bits/B}) = 256\ \text{MBits/sec},
\end{aligned}
\tag{4.1}
$$

and the byte file sink storing `libpcap` data at

$$
\begin{aligned}
R_{\text{Libpcap}} &= R_{\text{Samp}} \times N_{\text{Libpcap Size}} \times N_{\text{Byte Size}}, \\
R_{\text{Libpcap}} &= (4\ \text{MSamp/sec})(1\ \text{B/Samp})(8\ \text{Bits/B}), \\
R_{\text{Libpcap}} &= (4\ \text{MB/sec})(8\ \text{Bits/B}) = 32\ \text{MBits/sec}.
\end{aligned}
\tag{4.2}
$$

This means the air monitor was storing data at R_{Store} =68 MB/sec ($2 \times R_{\text{Complex}} + R_{\text{Libpcap}}$), not including the 3 statistical files, the binary fingerprint file being written, the RZUS-Bsticks transmitting bursts, and background computer processes.

The original `libpcap` file *control4-sample.pcap* contained N_{Packets} =407 packets, but only N_{Packets} =239 packets were replayed at T_{Burst} =10 msec intervals by *zbreplay* without the acknowledgement (ACK) packets. Table 4.1 is an illustration displaying the minimum, maximum, and average byte length of each IEEE 802.15.4 data packet within *control4-sample.pcap*. The `libpcap` table consists of:

- - *Packets* - The overall packet count and statistical data for $N_{\text{Total Packets}}$ packets regardless of byte length in the `libpcap` file
- - *0-19* - The packet count and statistical data for $N_{\text{0-19 Packets}}$ packets that are between 0 to 19 bytes long. The overall percentage of packets between 0 to 19 bytes long is $\frac{N_{\text{0-19 Packets}}}{N_{\text{Total Packets}}}$
- - *20-39* - The packet count and statistical data for $N_{\text{20-39 Packets}}$ packets that are between 20 to 39 bytes long. The overall percentage of packets between 20 to 39

bytes long is $\frac{N_{\text{20-39 Packets}}}{N_{\text{Total Packets}}}$

- - *40-79* - The packet count and statistical data for $N_{\text{40-79 Packets}}$ packets that are between 40 to 70 bytes long. The overall percentage of packets between 40 to 79 bytes long is $\frac{N_{\text{40-79 Packets}}}{N_{\text{Total Packets}}}$
- - *80-159* - The packet count and statistical data for $N_{\text{80-159 Packets}}$ packets that are between 80 to 159 bytes long. The overall percentage of packets between 80 to 159 bytes long is $\frac{N_{\text{80-159 Packets}}}{N_{\text{Total Packets}}}$

Table 4.1. Composition of *control4-sample.pcap* With and Without ACK Packets

Original IEEE 802.15.4 Libpcap Data With ACK Packets						
Packet Lengths			Average Val (B)	Min Val(B)	Max Val (B)	Packet Count
	Total Packets	100.00%	36.44	5	90	407
	0-19	43.24%	5.33	5	18	176
	20-39	1.47%	26.67	21	28	6
	40-79	40.54%	51.87	45	73	165
	80-159	14.74%	86.27	80	90	60
Original IEEE 802.15.4 Libpcap Data Without ACK Packets						
Packet Lengths			Average Val (B)	Min Val(B)	Max Val (B)	Packet Count
	Total Packets	100.00%	58.55	10	90	239
	0-19	3.35%	12.25	10	18	8
	20-39	2.51%	26.67	21	28	6
	40-79	69.04%	51.87	45	73	165
	80-159	25.10%	86.27	80	90	60

Each packet's physical signal burst period T_{Packet} can be approximately calculated using the packet byte length N_{Packet}, the SHR byte length N_{SHR}, the PHY Header (PHR) byte length N_{PHR}, and IEEE 802.15.4 Offset-Quadrature Phase Shift Keying (O-QPSK) bit rate

R_b as

$$
\begin{aligned}
T_{\text{Packet}} &\approx \frac{(N_{\text{Packet}} + N_{\text{SHR}} + N_{\text{PHR}})\big(N_{\text{Byte Size}}\big)}{R_b}, \\
T_{\text{Packet}} &\approx \frac{(N_{\text{Packet}} + 5\text{ B} + 1\text{ B})(8\text{ Bits/B})}{250\text{kBits/sec}}, \\
T_{\text{Packet}} &\approx \frac{(N_{\text{Packet}} + 6\text{ B})\text{ sec}}{31.25\text{kB}},
\end{aligned}
\tag{4.3}
$$

where the longest single burst period for a ZigBee device with a maximum packet length of $N_{\text{Packet}} = 127$ bytes would be $T_{\text{Packet}} \approx 4.26$ msec per the IEEE 802.15.4 standard. According to Table 4.1, the packets transmitted from the libpcap file varied in length from $N_{\text{Packet}} = 10$ to 90 bytes. This caused the transmitted burst-to-burst replay period to shift between 10.51 msec $\leq T_{\text{TX Burst}} \leq$ 13.07 msec due to the transmitted packets physical signal burst period varying anywhere between 0.51 msec $\leq T_{\text{Packet}} \leq$ 3.07 msec.

A bash script was created to consecutively replay the `libpcap` file 8-times to generate $N_{\text{Bursts}} = 1{,}912$ bursts on each device. The file replay interval T_{Replay} was dependent the operating system's current workload. The period varied anywhere between 0.179 sec $\leq T_{\text{Replay}} \leq$ 0.61 sec, but generally kept around $T_{\text{Replay}} \approx 0.58$ sec between each successive replay. Refer to Appendix A for In-Phase and Quadrature-Phase (I/Q) and power plot collection figures for each device. The ideal reconstructed packet composition for $N_{\text{Total Packets}} = 19{,}120$ packets on Table 4.2 is a baseline metric used to compare the detected data's segregated packet length segments cumulative ratios against. The Absolute Reconstructed Packet Ratio Deviation ($\%A_{\Delta}$) between each detected packet lengths cumulative ratio and the ideal packet lengths cumulative ratio listed on Table 4.2 as

$$
\%A_{\Delta} = |\%_{\text{Detected Packet Ratio}} - \%_{\text{Ideal Detected Packet Ratio}}| \tag{4.4}
$$

to see how much each packet length segment deviated from the ideal composition.

Table 4.2. Ideal Composition of $N_{\text{Total Packets}} = 19{,}120$ Detected Packets

Ideal Composition of Reconstructed IEEE 802.15.4 Libpcap Data Without ACK Packets						
Packet Lengths			Average Val (B)	Min Val(B)	Max Val (B)	Packet Count
	Total Packets	***100.00%***	*58.55*	*10*	*90*	*19120*
	0-19	***3.35%***	*12.25*	*10*	*18*	*640*
	20-39	***2.51%***	*26.67*	*21*	*28*	*480*
	40-79	***69.04%***	*51.87*	*45*	*73*	*13200*
	80-159	***25.10%***	*86.27*	*80*	*90*	*4800*

The overall statistical data collected from all the RZUSBstick's transmitting $N_{\text{Overall}} =$ 19,120 overall bursts is below on Table 4.3. Table 4.3 contains the minimum, maximum, and average of the overall collections results listed below as::

- *Time (sec)* - Timestamp when the first and last recovered packet were captured in the `libpcap` file.
- *Packets Detected* - The packet count and statistical data for N_{Detected} packets for all of the detected packets within the *preamble_sink* block. The Overall Packet Detection Percent ($\%D$) is $\frac{N_{\text{Detected}}}{N_{\text{Overall}}}$
- *Short Packets* - The packet count and statistical data for N_{Short} packets for detected packets with frame lengths shorter than minimum frame length of 9 bytes within the *preamble_sink* block (See Figure 2.3). The overall percentage of short packets is $\frac{N_{\text{Short}}}{N_{\text{Overall}}}$
- *Bad Cyclic Redundancy Check (CRC) Packets* - The packet count and statistical data for $N_{\text{CRC Bad}}$ packets for detected packets that contain data errors detected during a CRC-16 check within the *preamble_sink* block. The overall percentage of packets that failed the CRC-16 data check is $\frac{N_{\text{CRC Bad}}}{N_{\text{Overall}}}$
- *Good CRC Packets* - The packet count and statistical data for $N_{\text{CRC Good}}$ packets for detected packets that passed the CRC-16 check within the *preamble_sink* block.

The Overall Acurate Packet Reconstruction Percent (%R) that passed the CRC-16 data check is $\frac{N_{\text{CRC Good}}}{N_{\text{Overall}}}$

- *Preambles Accepted* - The burst count and statistical data for N_{Accepted} bursts for detected IEEE 802.15.4 SHR bursts within the *preamble_sink* block. The overall percentage of detected IEEE 802.15.4 SHR bursts is $\frac{N_{\text{Accepted}}}{N_{\text{Overall}}}$

- *Preambles Rejected* - The burst count and statistical data for N_{Rejected} bursts for rejected IEEE 802.15.4 SHR bursts within the *preamble_sink* block. The overall percentage of rejected IEEE 802.15.4 SHR bursts is $\frac{N_{\text{Rejected}}}{N_{\text{Overall}}}$

- *Total Processed Fingerprints* - The fingerprint count and statistical data for $N_{\text{Fingerprint}}$ fingerprints generated in the *Dna detector ccf* block from detected IEEE 802.15.4 SHR bursts within the *preamble_sink block*. The Overall Fingerprinted Percent (%F) of IEEE 802.15.4 SHR bursts is $\frac{N_{\text{Fingerprint}}}{N_{\text{Overall}}}$

- *% Fingerprints Processed* - The ratio between the $N_{\text{Fingerprint}}$ generated fingerprints within the *Dna detector ccf* block and the accepted IEEE 802.15.4 SHR bursts within the *preamble_sink* block is computed as $\frac{N_{\text{Fingerprint}}}{N_{\text{Accepted}}}$

The collection results of the $N_d = 10$ RZUSBsticks displayed on Table 4.3 shows the packet detection rate %D= 97.93% from the $N_{Overall} = 19{,}120$ transmitted bursts within an overall average $T_{Collect} = 25.691$ sec transmission period. %R= 97.92% of the IEEE 802.15.4 data packets passed CRC-16 verification and 97.85% IEEE 802.15.4 SHR waveform bursts were detected from the overall transmitted bursts. %F= 97.48% of the transmitted bursts were fingerprinted within the *Dna detector ccf* block. 99.63% of the $N_{\text{Accepted}} = 18{,}708$ accepted IEEE 802.15.4 SHR bursts were fingerprinted and used for device discrimination.

The *Dna detector ccf* block performs device discrimination using invalid data(i.e. identity matrices and vectors of one's) whenever trained data is not uploaded into the

Table 4.3. Overall Collection Performance for $N_d = 10$ Devices

				Avg	Min	Max	Overall Numbers
Time (sec)				***25.691***	***25.534***	***25.89***	
Packets Transmitted			***100.00%***	*1912*	*1912*	*1912*	*19120*
Preamble Sink Detected Bursts	Packet Data	Total Packets Detected(D%)	***97.93%***	*1872.5*	*1820*	*1910*	*18725*
		Short Packets	***0.01%***	*0.1*	*0*	*1*	*1*
		Bad CRC Packets	***0.01%***	*0.1*	*0*	*1*	*1*
		Good CRC Packets (R%)	***97.92%***	*1872.3*	*1820*	*1910*	*18723*
	SHR	Preambles Accepted	***97.85%***	*1870.8*	*1820*	*1909*	*18708*
		Preambles Rejected	***0.09%***	*1.7*	*0*	*4*	*17*
Dna detector Fingerprinted SHR	Total Processed Fingerprints(F%)		***97.48%***	*1863.9*	*1801*	*1909*	*18639*
	% Preambles Fingerprinted		***99.63%***	*99.63%*	*98.96%*	*100.00%*	
Reconstructed IEEE 802.15.4 Libpcap Packet Data							
				Average Val (B)	**Min Val(B)**	**Max Val (B)**	**Overall Packet Count**
Packet Lengths		Total Packets	***100.00%***	*58.572*	*1*	*90*	*18725*
		0-19	***3.33%***	*12.219*	*1*	*18*	*624*
		20-39	***2.50%***	*26.687*	*21*	*28*	*469*
		40-79	***69.03%***	*51.877*	*45*	*73*	*12926*
		80-159	***25.13%***	*86.269*	*80*	*90*	*4706*

block. The air monitor processed a IEEE 802.15.4 SHR waveform once a complete data packet was processed. It generally took the air monitor between 0.46 msec $\leq T_{\text{MDA}} \leq$ 1.5 msec from the time a burst was detected to the time a device was classified.

The detected overall packet length cumulative ratio on Table 4.3 deviated from the ideal values on Table 4.2 on average by $\%A_{\Delta}$= 0.0425% for all of the packet lengths. 97.50% ($N_{0-19} = 624$) of the 0 to 19 byte length packets were recovered with an $\%A_{\Delta\text{Diff 0-19}} = 0.02\%$ packet ratio deviation; 97.71% ($N_{20-39} = 469$) of the 20 to 39 byte length packets were recovered with an $\%A_{\Delta\text{Diff 20-39}} = 0.01\%$ packet ratio deviation; 97.92% ($N_{40-79} = 12{,}926$) of the 40 to 79 byte length packets were recovered with an $\%A_{\Delta\text{Diff 40-79}} = 0.01\%$ packet ratio deviation; and 98.04% ($N_{80-159} = 4{,}706$) of the 80 to 159 byte length packets were recovered with an $\%A_{\Delta\text{Diff 80-159}} = 0.13\%$ packet ratio deviation. Overall, 99.99% ($\frac{N_{\text{CRC-16}}}{N_{\text{Detected}}}$) of the $N_{\text{Detected}} = 18{,}725$ detected packets were CRC-16 verified and contained appropriate frame lengths.

4.2 GNU Radio Air Monitor Operational Performance Analysis

The same metrics used in Section 4.1 were utilized to assess the NRT operational performance of the air monitor. The difference in this test is that the air monitor did not store any collected fingerprints as binary data, did not store any complex binary data, and loaded the air monitors fingerprint trained MDA_{Air} into the *Dna detector ccf* block.

The operational results of the $N_d = 10$ RZUSBsticks displayed on Table 4.4 shows the packet detection rate increased to $\%D = 99.99\%$ from the $N_{\text{Overall}} = 19{,}120$ transmitted bursts within an overall average $T_{Collect} = 25.1958$ sec transmission period. The overall IEEE 802.15.4 data packets that passed CRC-16 verification displayed an improvement to $\%R = 99.96\%$ and 99.91% of the IEEE 802.15.4 SHR waveform bursts were detected from the overall transmitted bursts. The overall fingerprinted bursts within the *Dna*

Table 4.4. Overall Operational Performance for $N_d = 10$ Devices

Time (sec)				25.1958	25.108	25.309	
Packets Transmitted			100.00%	1912	1912	1912	19120
Preamble Sink Detected Bursts	Packet Data	Total Packets Detected(D%)	99.99%	1911.8	1911	1913	19118
		Short Packets	0.02%	0.4	0	1	4
		Bad CRC Packets	0.01%	0.2	0	1	2
		Good CRC Packets(R%)	99.96%	1911.2	1910	1912	19112
	SHR	Preambles Accepted	99.91%	1910.3	1908	1912	19103
		Preambles Rejected	0.08%	1.5	0	3	15
Dna detector Fingerprinted SHR	Total Processed Fingerprints(F%)		99.88%	1909.7	1907	1912	19097
	% Preambles Fingerprinted		99.97%	99.97%	99.84%	100.00%	
Reconstructed IEEE 802.15.4 Libpcap Packet Data							
				Average Val (B)	Min Val(B)	Max Val (B)	Overall Packet Count
Packet Lengths		Total Packets	100.00%	58.538	1	90	19118
		0-19	3.37%	12.196	1	18	644
		20-39	2.51%	26.67	21	28	480
		40-79	69.02%	51.872	45	73	13195
		80-159	25.10%	86.27	80	90	4799

detector ccf block increased to $\%F = 99.88\%$ during the operational trial. 99.97% of the $N_{Accepted} = 19{,}103$ accepted IEEE 802.15.4 SHR bursts were fingerprinted and used for device discrimination. The time a burst was detected to the time a device was discriminated was not measured for this test as it was assumed to be 0.45 msec $\leq T_{\text{MDA}} \leq 1.5$ msec or better.

The detected overall packet length cumulative ratio on Table 4.3 compared against the ideal values on Table 4.2 deviated on average by $\%A_{\Delta} = 0.035\%$ for all of the packet lengths during the operational test. 100.63% ($N_{0-19} = 644$) of the 0 to 19 byte length packets were recovered with an $\%A_{\Delta\text{Diff 0-19}} = 0.02\%$ packet ratio deviation; 100.0% ($N_{20-39} = 480$) of the 20 to 39 byte length packets were recovered with an $\%A_{\Delta\text{Diff 20-39}} = 0.02\%$ packet ratio deviation; 99.96% ($N_{40-79} = 13{,}195$) of the 40 to 79 byte length packets were recovered with an $\%A_{\Delta\text{Diff 40-79}} = 0.01\%$ packet ratio deviation;

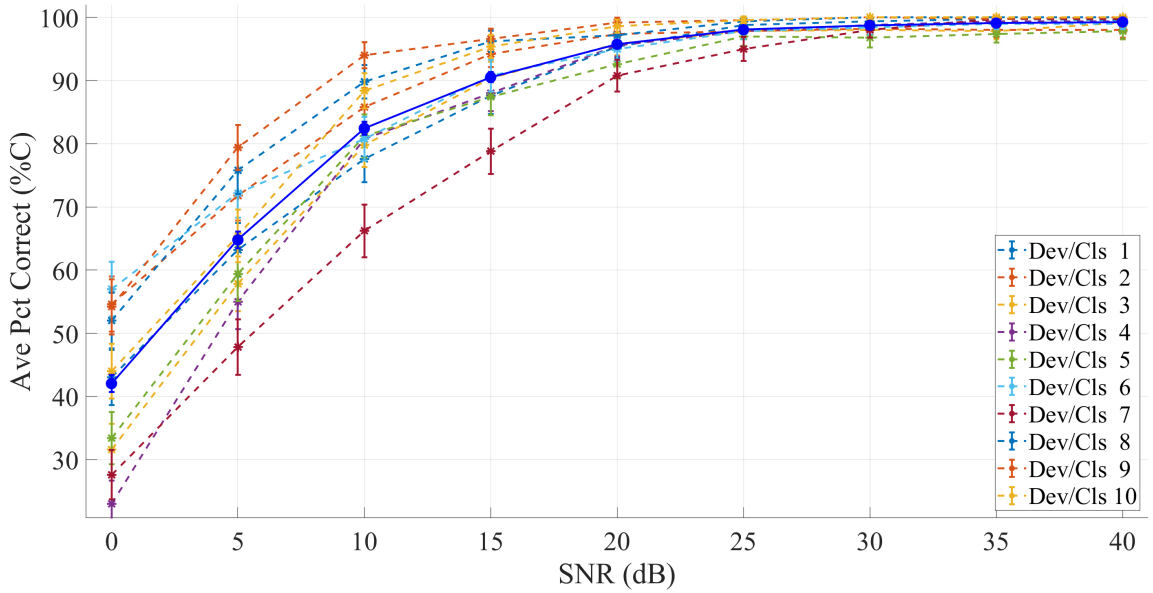
and 99.98% ($N_{80-159} = 4{,}799$) of the 80 to 159 byte length packets were recovered with an $\%A_{\Delta \text{Diff 80-159}} = 0.1\%$ packet ratio deviation. This experiment resulted in 99.97% ($\frac{N_{\text{CRC-16}}}{N_{\text{Detected}}}$) of the N_{Detected} =19,118 detected packets were CRC-16 verified with appropriate frame lengths.

4.3 Air Monitor MDA/ML Classification Model Development

An estimative $\text{MDA/ML}_{\text{Est}}$ performance model between 0 dB ≤ Signal-to-Noise Ratio (SNR) ≤ 40 dB for the $N_d = 10$ RZUSBsticks was developed using the methods previously listed in Sections 3.4 and 3.3.1. The Average Percent Correct Classification ($\%C$) is the percent of times that the classifier correctly classified a device. Table 4.5 contains the computed $\%C$ for each set of testing fingerprints within the SNR model. The range was chosen because it was assumed that the air monitor would operate somewhere within the modeled SNR range. The $\text{MDA/ML}_{\text{Est}}$ model for the $N_d = 10$ devices shows that the $\%C \geq 90.00\%$ at an SNR = 15 dB.

After the MATLAB $\text{MDA/ML}_{\text{Est}}$ model was built, the SNR of the $N_d = 10$ RZUSBsticks was measured before any of the Radio Frequency (RF) air monitor's fingerprints were used for $\text{MDA/ML}_{\text{Air}}$ processing. The SNR varied between 31 dB ≤ SNR ≤ 35 dB with an overall collection mean SNR ≈ 33.571 dB. Comparing the collected devices SNR to Table 4.5, the air monitors $\%C$ was estimated to be between $98.76\% \leq \%C \leq 99.10\%$. The air monitor fingerprint trained $\text{MDA/ML}_{\text{Air}}$ model revealed that the $\%C$ varied between $98.20\% \leq \%C \leq 100.00\%$ with an overall $\%C = 99.64$ as shown on the Confusion Matrix (CM) on Table 4.6. The CM contains the $\%C$ of each RZUSBstick on the highlighted diagonal headings while the non-diagonal values contains the Individual % Incorrect Classification ($\%I$) of each misclassified device (i.e. device 1 classified as device 2,3,etc).

Table 4.5. Estimative RF-DNA MDA/ML Cross Classification Performance Model from 0 dB ≤ SNR = 40 dB



SNR (dB)	0	5	10	15	20	25	30	35	40
Testing % Correct	*42.04%*	*64.78%*	*82.44%*	*90.54%*	*95.76%*	*98.06%*	*98.76%*	*99.10%*	*99.28%*

Table 4.6. Confusion Matrix $N_d = 10$ Class Problem at SNR ≈ 33.571 dB

Collected Model	Classified Device (%)										
	Device	1	2	3	4	5	6	7	8	9	10
Input Device (%)	1	***99.40%***	*0.00%*	*0.00%*	*0.60%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*
	2	*0.00%*	***98.20%***	*0.00%*	*0.00%*	*1.80%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*
	3	*0.00%*	*0.00%*	***99.80%***	*0.00%*	*0.00%*	*0.20%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*
	4	*0.20%*	*0.00%*	*0.00%*	***99.80%***	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*
	5	*0.00%*	*0.40%*	*0.00%*	*0.00%*	***99.60%***	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*
	6	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	***100.00%***	*0.00%*	*0.00%*	*0.00%*	*0.00%*
	7	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	***100.00%***	*0.00%*	*0.00%*	*0.00%*
	8	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	***100.00%***	*0.00%*	*0.00%*
	9	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	***100.00%***	*0.00%*
	10	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.40%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	***99.60%***
Min %C		***98.20%***									
Max %C		***100.00%***									
Overall %C		***99.64%***									

4.4 NRT Device Discrimination Analysis

Tables 4.7 and 4.8 were created to assess how well the RF air monitor classified and discriminated between devices in NRT after MDA_{Air} data was uploaded. Table 4.7 is a

raw CM consisting of the cumulative totals collected for each device. The highlighted diagonal entries represent the number of times each time each device was correctly classified and the non-diagonal values contains the the number of times the device was incorrectly classified (i.e. device 1 classified as device 2,3,etc N times). The cumulative sums at the right end of each row on Table 4.7 represent the total number of times each RZUSBstick was detected. The cumulative sums at the bottom of each column on Table 4.7 represent the total number of times a particular classification for a device was declared.

Table 4.7. Operational NRT Device Discrimination Raw CM Totals for $N_d = 10$ Devices

RF-DNA Totals	Classified Device Totals											Input Device Totals
	Device	1	2	3	4	5	6	7	8	9	10	
Input Device Totals	1	**1574**	0	0	335	0	0	0	0	0	0	**1909**
	2	12	**1850**	0	0	8	0	0	0	0	40	**1910**
	3	0	0	**1910**	0	0	0	0	1	0	0	**1911**
	4	0	0	0	**1908**	0	0	0	0	0	0	**1908**
	5	97	1	0	0	**1814**	0	0	0	0	0	**1912**
	6	0	0	0	0	0	**1880**	1	0	9	19	**1909**
	7	0	0	0	0	0	0	**1885**	0	25	0	**1910**
	8	0	0	0	0	0	0	0	**1912**	0	0	**1912**
	9	0	0	0	0	0	0	9	1	**1899**	0	**1909**
	10	0	0	0	0	0	27	0	0	1	**1879**	**1907**
Classified Device Totals		**1683**	**1851**	**1910**	**2243**	**1822**	**1907**	**1895**	**1914**	**1934**	**1938**	**19097**

The CM depicted on Table 4.8 was created with the N totals within each element in Table 4.7. Each element's percentage ($\%_{\text{Device,Class}}$) was calculated using,

$$\%_{\text{Device,Class}} = \frac{N_{\text{Device,Class}}}{\sum_{m=1}^{10} N_{\text{Device},m}}, \quad \text{Device} = \{1,\ldots,10\} \text{ and Class} = \{1,\ldots,10\}, \tag{4.5}$$

where the $\%C$ and $\%I$ of each device in Table 4.8 is

$$\%_{\text{Device,Class}} = \begin{cases} \%C, & \text{Device=Class} \\ \%I, & \text{otherwise} \end{cases}, \tag{4.6}$$

The operational tests classification results for the $N_d = 10$ RZUSBsticks varied between $82.45\% \leq \%C \leq 100.00\%$ with an overall $\%C = 96.93\%$. Table 4.7 was used to create the CM below on Table 4.8 along with a joint Probability Mass Function (PMF) Table in Appendix B for further analysis.

Table 4.8. Operational NRT Device Discrimination $\%C$ CM for $N_d = 10$ Devices

RF-DNA		Classified Device (%)									
	Device	1	2	3	4	5	6	7	8	9	10
Input Device (%)	1	***82.45%***	*0.00%*	*0.00%*	*17.55%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*
	2	*0.63%*	***96.86%***	*0.00%*	*0.00%*	*0.42%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*2.09%*
	3	*0.00%*	*0.00%*	***99.95%***	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.05%*	*0.00%*	*0.00%*
	4	*0.00%*	*0.00%*	*0.00%*	***100.00%***	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*
	5	*5.07%*	*0.05%*	*0.00%*	*0.00%*	***94.87%***	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*
	6	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	***98.48%***	*0.05%*	*0.00%*	*0.47%*	*1.00%*
	7	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	***98.69%***	*0.00%*	*1.31%*	*0.00%*
	8	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	***100.00%***	*0.00%*	*0.00%*
	9	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.47%*	*0.05%*	***99.48%***	*0.00%*
	10	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*1.42%*	*0.00%*	*0.00%*	*0.05%*	***98.53%***
Min %C		***82.45%***									
Max %C		***100.00%***									
Overall %C		***96.93%***									

V. Conclusion

This chapter provides a summary of the research activities conducted, research contributions, and recommendations for future research.

5.1 Results Summary

Wireless device usage is widespread and increasing as more consumers embrace Internet of Things (IoT) devices. ZigBee is a popular choice amongst consumers because of it's low-cost, low-power, and low-bit rate communications are ideal for Wireless Sensor Network(s) (WSN). ZigBee Low-Rate Wireless Personal Area Network(s) (LR-WPAN) are extensively used in sensor networks, cyber-physical systems, and smart buildings [1]. With this use comes a heightened risk of unauthorized data access and modifications. Such problems occur when rogue users or devices bypass security measures by spoofing bit-level credentials. Prior research has shown fingerprinting to be effective as an additional form of Physical Layer (PHY) security against malicious attacks [6, 8, 12, 13, 16]. While proven effective through MATLAB simulation-based classification, this research aims to examine the effectiveness of fingerprinting and device discrimination in Near Real-Time (NRT) using an Radio Frequency (RF) air monitor employing an Universal Software Radio Peripheral(s) (USRP) Software-Defined Radio(s) (SDR) and open-source software.

5.2 Research Contribution

An RF air monitor for fingerprinting and discriminating devices in NRT is feasible and effective using trained Multiple Discriminant Analysis/Maximum Likelihood (MDA/ML) data. NRT Radio Frequency-Distinct Native Attribute (RF-DNA) Fingerprinting performance was first assessed by the air monitor's ability to capture and pro-

cess ZigBee bursts accurately and efficiently from the $N_d = 10$ RZUSBsticks while the systems was writing to the hard drive at a rate over $R_{\text{Store}} > 68$ MB/sec. There were some occasional buffer overflows that occurred because of the system resources allocated during the experiment. Despite the overflows, the air monitor acquired an Overall Packet Detection Percent ($\%D$) = 97.93% from the $N_{\text{Overall}} = 19{,}120$ transmitted ZigBee bursts. Each ZigBee contained a transmission period between 10.51 msec $\leq T_{\text{TX Burst}} \leq$ 13.07 msec intervals. During the collection trial, the RF air monitor achieved an Overall Acurate Packet Reconstruction Percent ($\%R$) = 97.92% from the transmitted ZigBee data; 99.99% of the detected $N_{\text{Detected}} = 18{,}725$ ZigBee PHY Service Data Unit (PSDU) packets were properly reconstructed (i.e. passed Cyclic Redundancy Check (CRC)-16 verification); and the overall mean Absolute Reconstructed Packet Ratio Deviation ($\%A_{\Delta}$) was 0.0425% from the ideal reconstructed packet composition. The RF air monitor attained an Overall Fingerprinted Percent ($\%F$) = 97.48% from the overall transmitted Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 Synchronization Headers (SHRs) and 99.65% of the N_{Accepted} =18,708 accepted IEEE 802.15.4 SHRs bursts were fingerprinted. The IEEE 802.15.4 SHR bursts were reliably RF-DNA fingerprinted within 0.45 msec $\leq T_{\text{MDA/ML}} \leq$ 1.5 msec after SHR burst detection. It's assumed that each device would be classified within the time same interval because non-trained data was used during the device discrimination process. Overall, the air monitor took an average T_{Collect} =25.651 sec to detect and process N_{Bursts} =1,912 ZigBee bursts transmitted from each RZUSBstick.

The focus of the second test was to assess the operational performance of the air monitor with trained MDA_{Air} data and the raw data storage options disabled. The same transmission conditions and performance metrics were used for the $N_d = 10$ devices as the initial experiment. The air monitor's overall detection performance increased to $\%D = 99.99\%$ from the $N_{\text{Overall}} = 19{,}120$ transmitted ZigBee bursts. Each

transmitted ZigBee bursts maintained the same transmission period between 10.51 msec $\leq T_{\text{TX Burst}} \leq$ 13.07 msec as the initial collection trial. The RF air monitor's overall ZigBee packet reconstruction performance increased with $\%R = 99.96\%$ from the transmitted ZigBee data; 99.97% of the $N_{\text{Detected}} = 19{,}118$ ZigBee PSDU packets were properly reconstructed; and the overall mean $\%A_{\Delta}$ was 0.035% from the ideal reconstructed packet composition. The RF air monitors fingerprinting numbers also increased during the operational trials with $\%F = 99.88\%$ from the overall transmitted IEEE 802.15.4 SHRs and 99.97% of the $N_{\text{Accepted}} = 19{,}103$ accepted SHRs bursts were fingerprinted. The amount of time it took to fingerprint an IEEE 802.15.4 burst was not measured for the second performance assessment, but was assumed to be 0.45 msec $\leq T_{\text{TX Burst}} \leq$ 1.5 msec or better. The average time the air monitor took to detect and process N_{Bursts} =1,912 ZigBee bursts dropped to T_{Collect} =25.198 sec. The overall performance of the RF air monitor improved across every examined performance metric.

An estimative MDA/ML_{Est} performance model was developed with fingerprints created by adding Additive White Gaussian Noise (AWGN) to the $N_d = 10$ ZigBee device collections to simulate an environment with an Signal-to-Noise Ratio (SNR) range between 0 dB $\leq$ SNR $\leq$ 40 dB in 5 dB increments. The MDA/ML_{Air} model trained by the air monitor's fingerprints were compared against the estimative MDA/ML_{Est} model. The ZigBee RF-DNA fingerprints generated by the air monitor were collected at SNR $\approx$ 33.571 dB. The air monitors RF-DNA MDA/ML_{Air} model produced a Average Percent Correct Classification ($\%C$) = 99.64% that well exceeded the estimative MDA/ML_{Est} model range 98.76% $\leq \%C \leq$ 99.10% at an 30 dB $\leq$ SNR $\leq$ 35 dB. The trained MDA_{Air} data created from the NRT RF-DNA fingerprints were uploaded into the air monitor for the second test.

The air monitors NRT classification performance was assessed by creating a Confusion Matrix (CM) from the statistical data generated when the RF air monitor

was fingerprinting and discriminating devices. The classification results for the N_d =10 RZUSBsticks varied between 82.45% $\leq \%C \leq$ 100.00% with an overall $\%C = 96.93\%$. The non-simulated NRT classification differed slightly from the RF air monitors trained model with a $\%C$ Deviation ($\%C_\Delta$) = 2.71% lower than the MDA/ML_{Air} $\%C = 99.64\%$. Similarly, the NRT classification performance fell within the 20 dB $\leq$ SNR $\leq$ 25 dB range of the estimative MDA/ML_{Est} that varied between 95.76% $\leq \%C \leq$ 98.06%.

5.3 Future Research Recommendation

This research provides as a proof-of-concept demonstration using reasonably priced SDR and open-source tools that can be used to implement an RF air monitor for ZigBee devices. NRT RF-DNA Fingerprinting and device discrimination was successfully demonstrated using a B205mini-i and GNU Radio. The work completed provides a foundation for future research to:

1. Replicate the Experiment With Different Distinct Native Attribute (DNA) Fingerprint Features: Alternate DNA fingerprinting techniques could easily be implemented into the current GNU Radio air monitor. For example, Constellation Based-Distinct Native Attributes (CB-DNA) based Fingerprinting and discrimination has been shown to be more effective than RF-DNA in previous ZigBee research [8]. The CB-DNA experiments could be replicated over-the-air in NRT to see how the NRT results compare to past research.

2. Consider NRT Discrimination For Various IEEE Standards: This research was possible because an existing IEEE 802.15.4 module was available on GNU Radio. Various IEEE standards have successfully been deployed in GNU Radio. Most of these modules are openly available on GitHub and could potentially be transformed into air monitor prototypes.

3. Consider Autonomous Model Training: The RF air monitor's ability to discriminate between devices was entirely dependent on the MDA/ML model developed offline in MATLAB. Creating a model in MATLAB is not ideal for an NRT system. Properly formatting the GNU Radio fingerprints so that MDA/ML model can be created takes some time. Research towards the development of an intelligently trained autonomous MDA/ML model could potentially lead to the development of a truly "stand-alone" air monitor.

Appendix A. Device Collection Figures

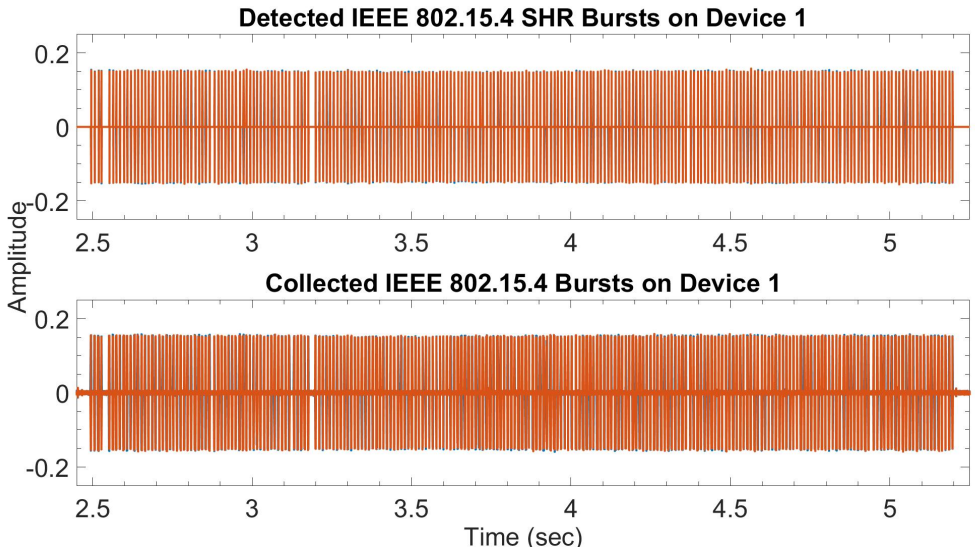


Figure A-1. I/Q Plot on Device 1 of N_{Bursts} =239 bursts from Libpcap File

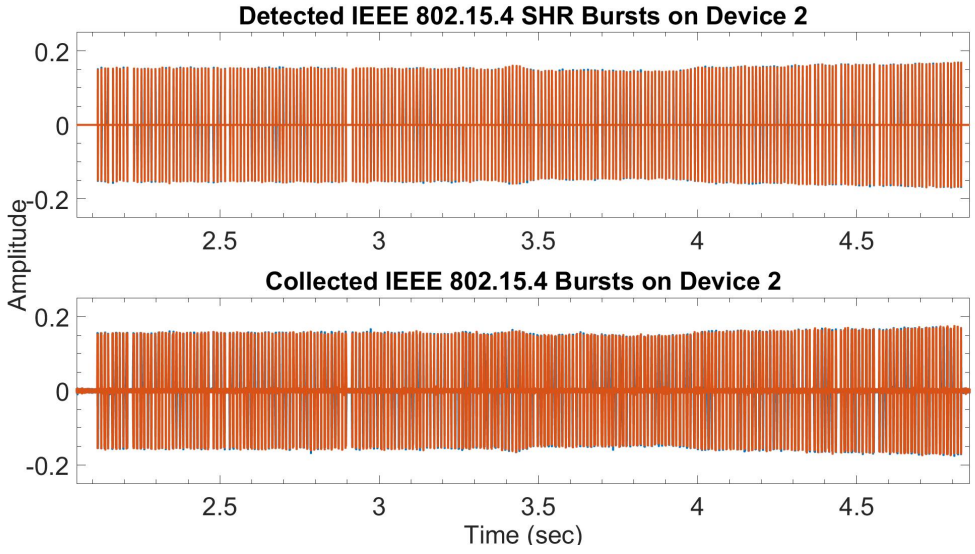


Figure A-2. I/Q Plot on Device 2 of N_{Bursts} =239 bursts from Libpcap File

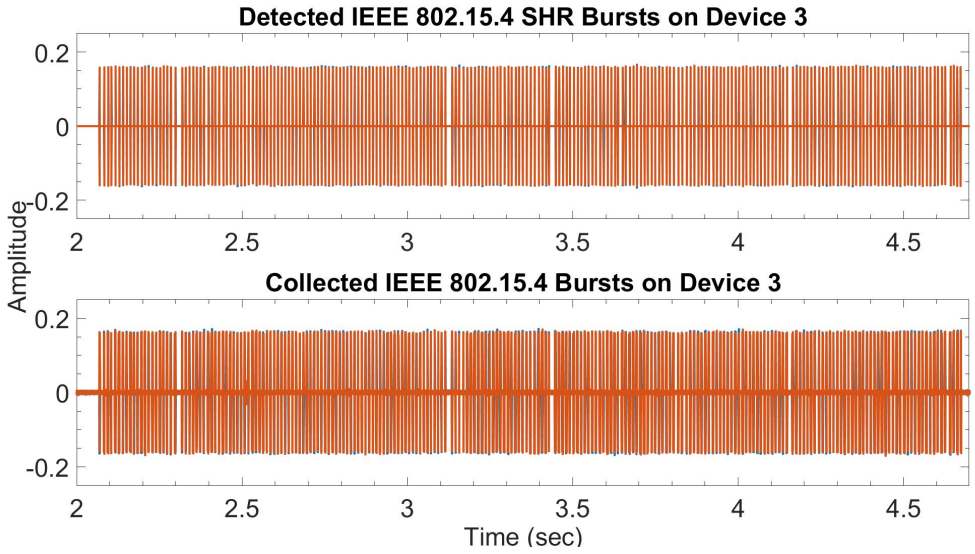


Figure A-3. I/Q Plot on Device 3 of N_{Bursts} =239 bursts from Libpcap File

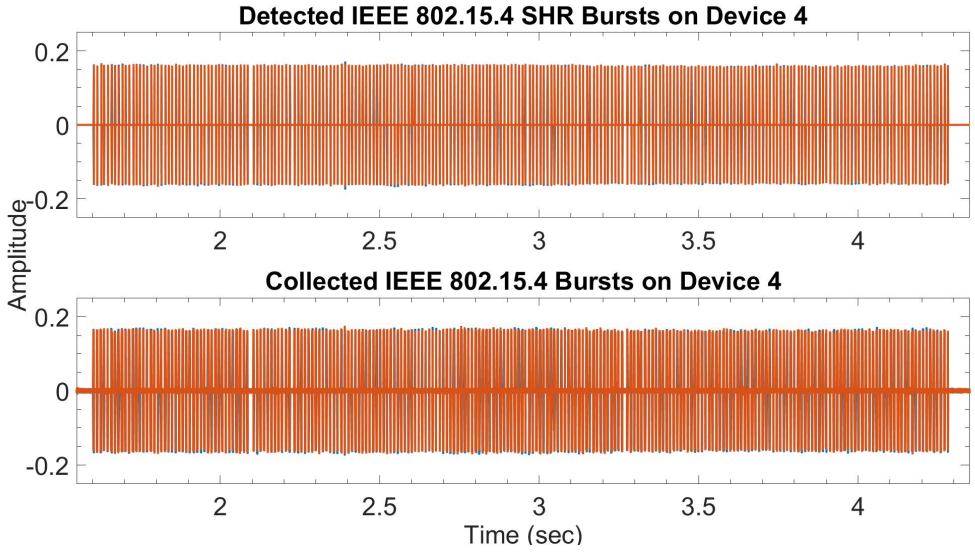


Figure A-4. I/Q Plot on Device 4 of N_{Bursts} =239 bursts from Libpcap File

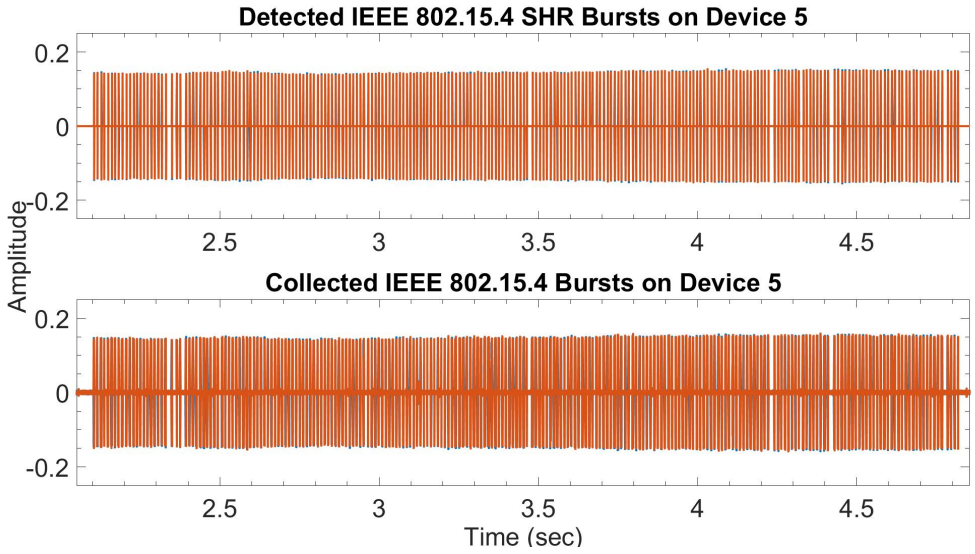


Figure A-5. I/Q Plot on Device 5 of N_{Bursts} =239 bursts from Libpcap File

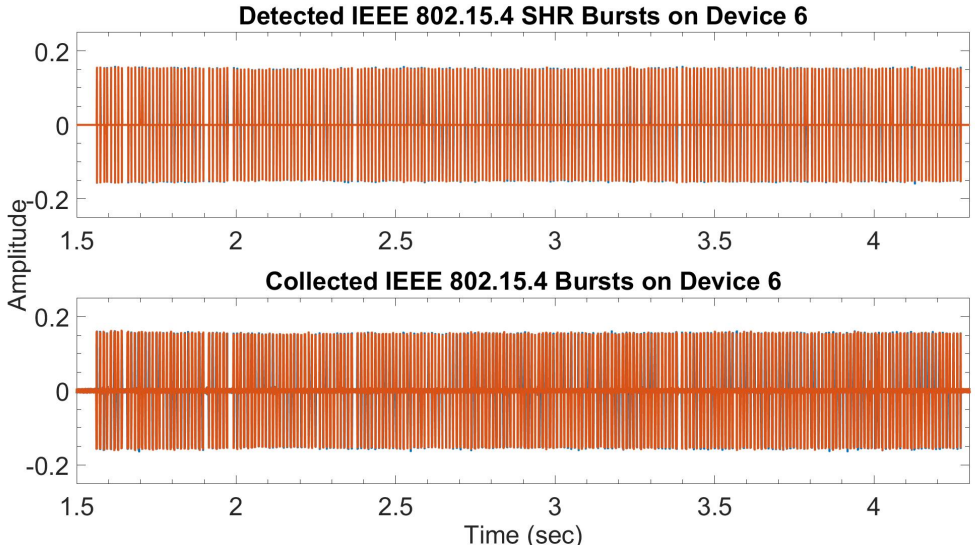


Figure A-6. I/Q Plot on Device 6 of N_{Bursts} =239 bursts from Libpcap File

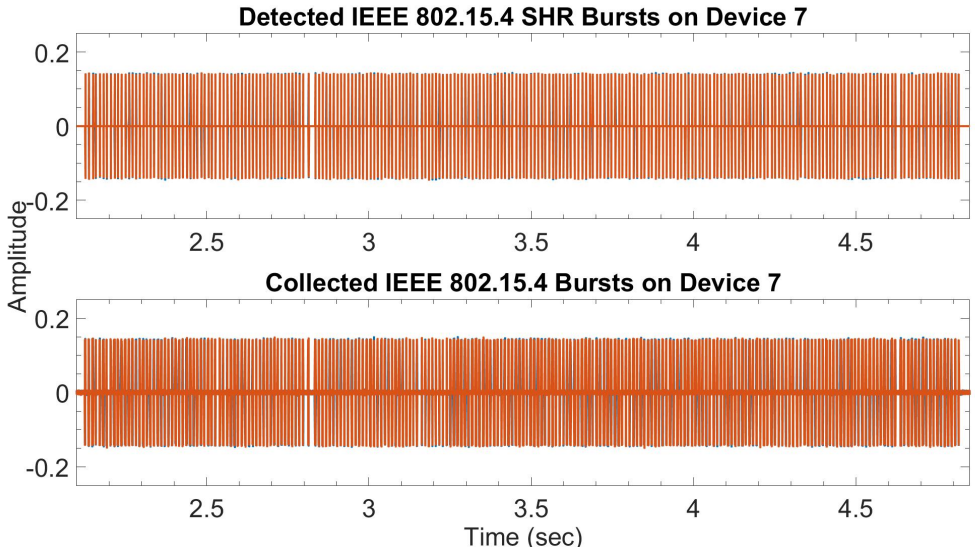


Figure A-7. I/Q Plot on Device 7 of N_{Bursts} =239 bursts from Libpcap File

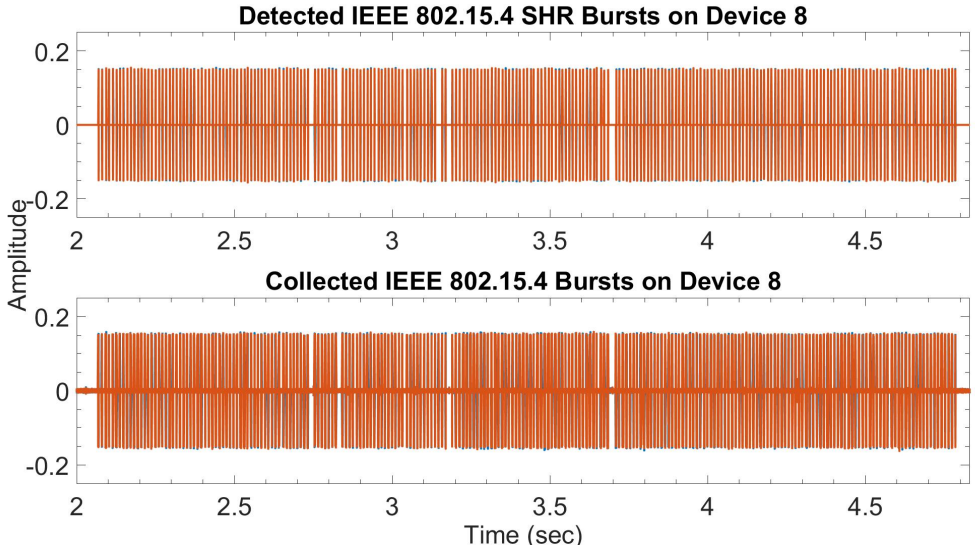


Figure A-8. I/Q Plot on Device 8 of N_{Bursts} =239 bursts from Libpcap File

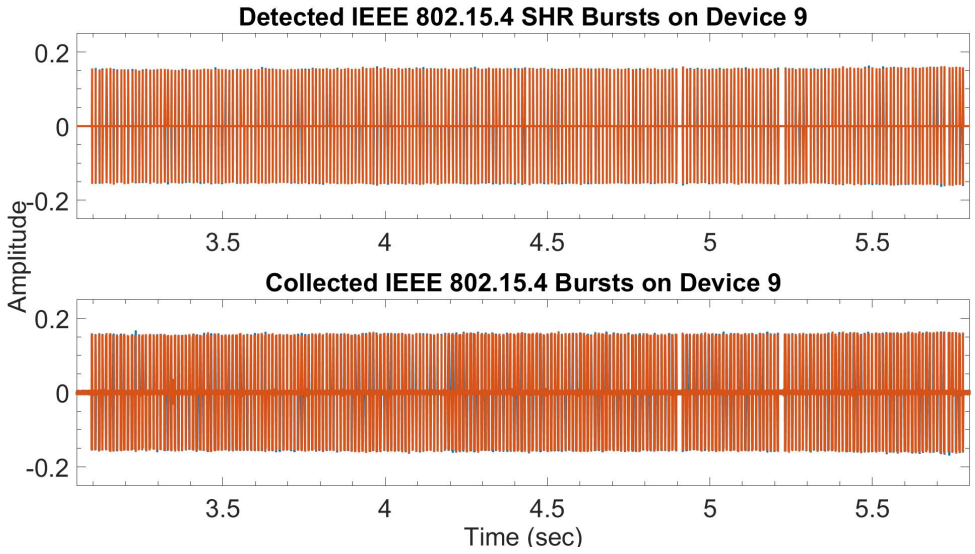


Figure A-9. I/Q Plot on Device 9 of N_{Bursts} =239 bursts from Libpcap File

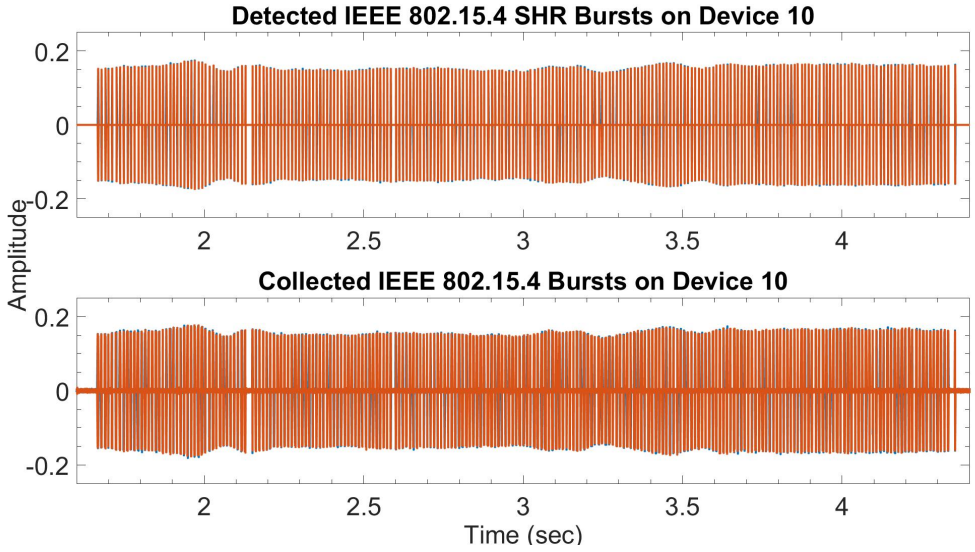
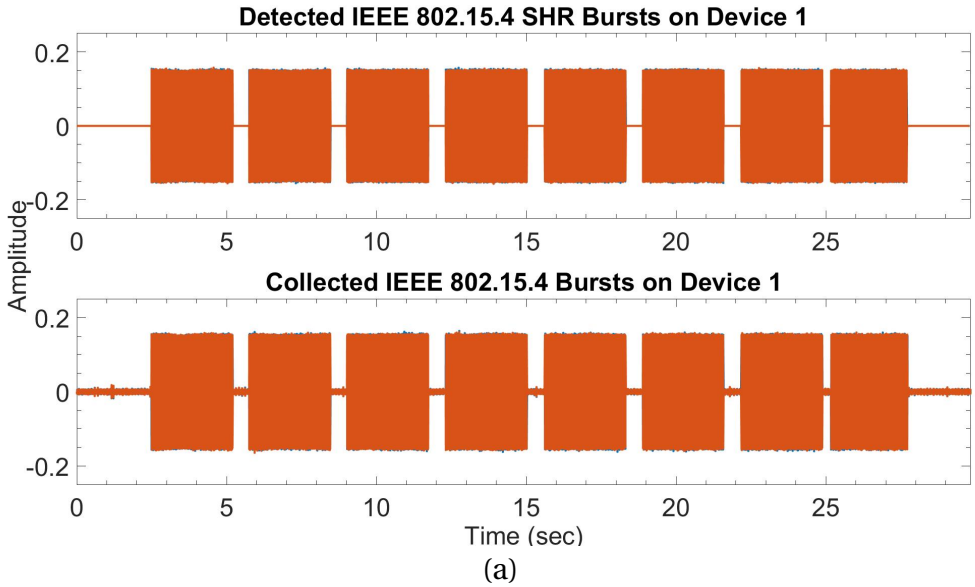
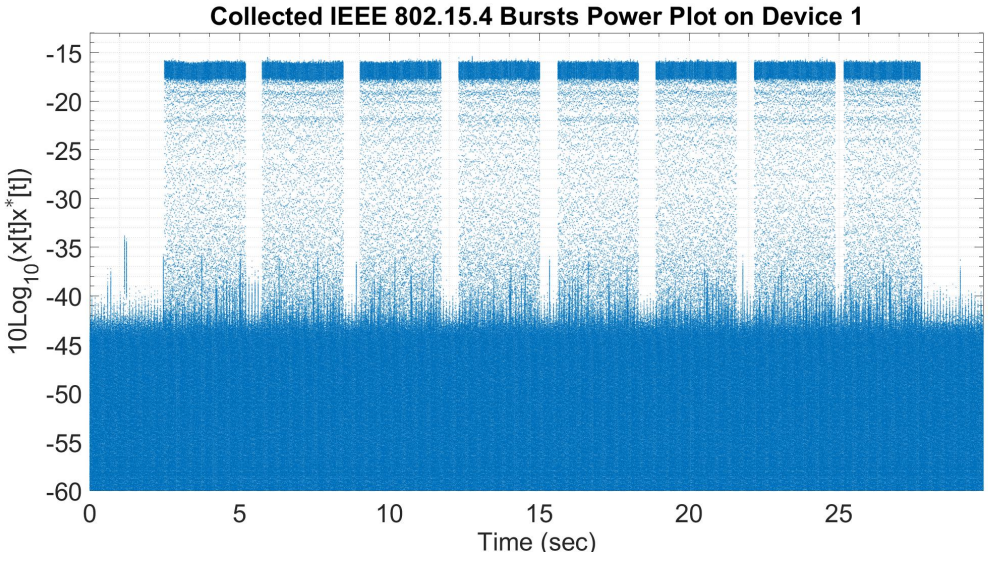


Figure A-10. I/Q Plot on Device 10 of N_{Bursts} =239 bursts from Libpcap File

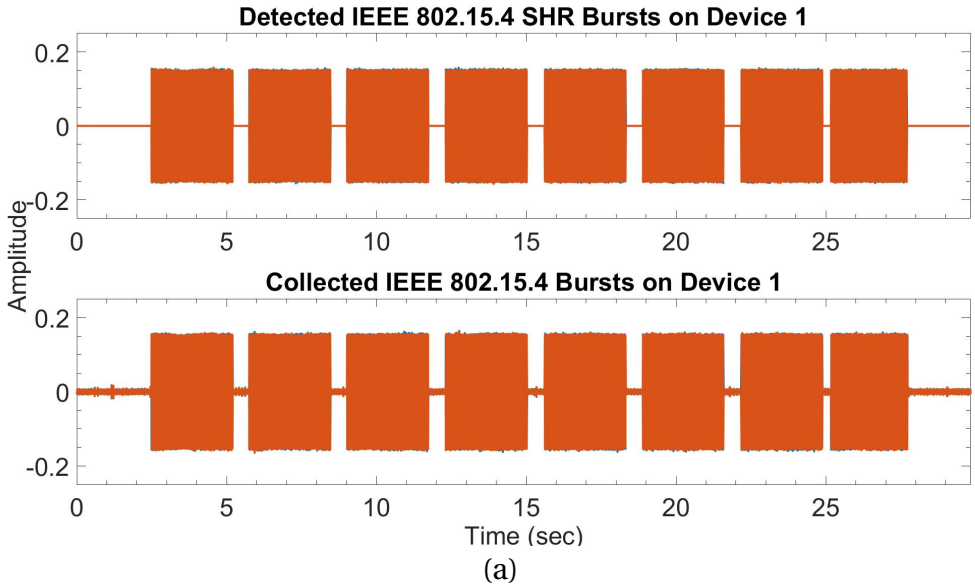


(a)

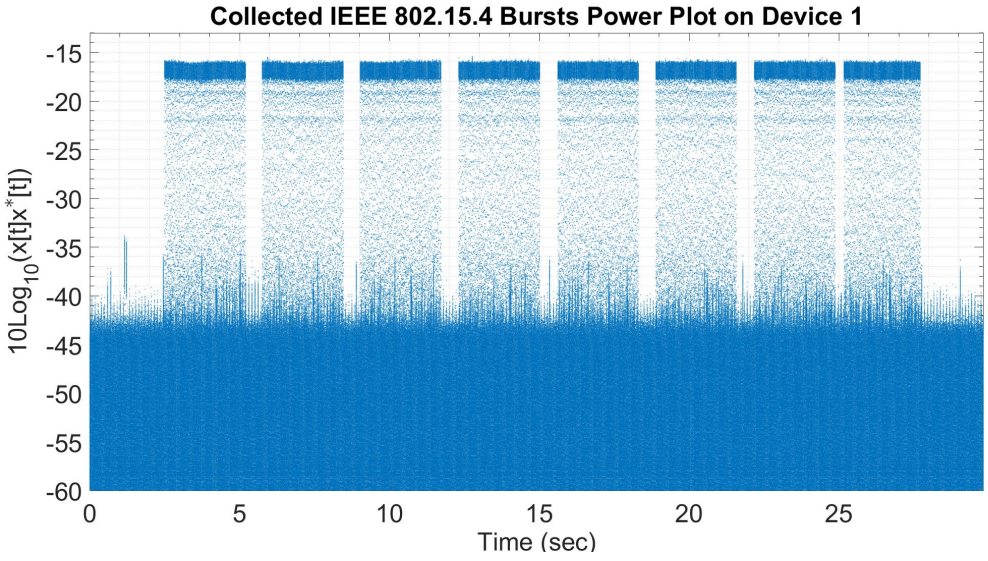


(b)

Figure A-11. (a) I/Q and (b) Power Plot on Device 1 of N_{Bursts} =1,912 bursts from Libpcap File Replayed 8-Times

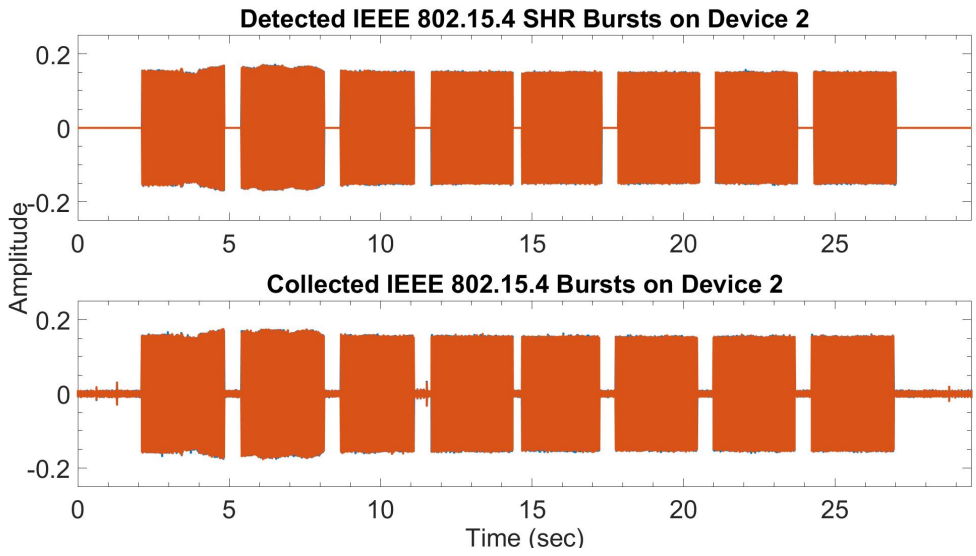


(a)

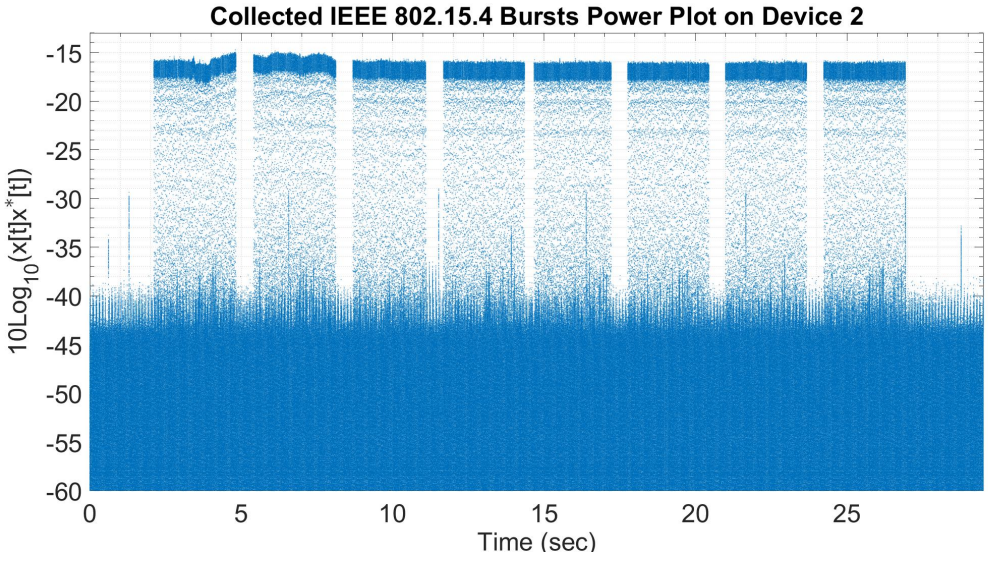


(b)

Figure A-12. (a) I/Q and (b) Power Plot on Device 1 of N_{Bursts} =1,912 bursts from Libpcap File Replayed 8-Times



(a)



(b)

Figure A-13. (a) I/Q and (b) Power Plot on Device 2 of N_{Bursts} =1,912 bursts from Libpcap File Replayed 8-Times

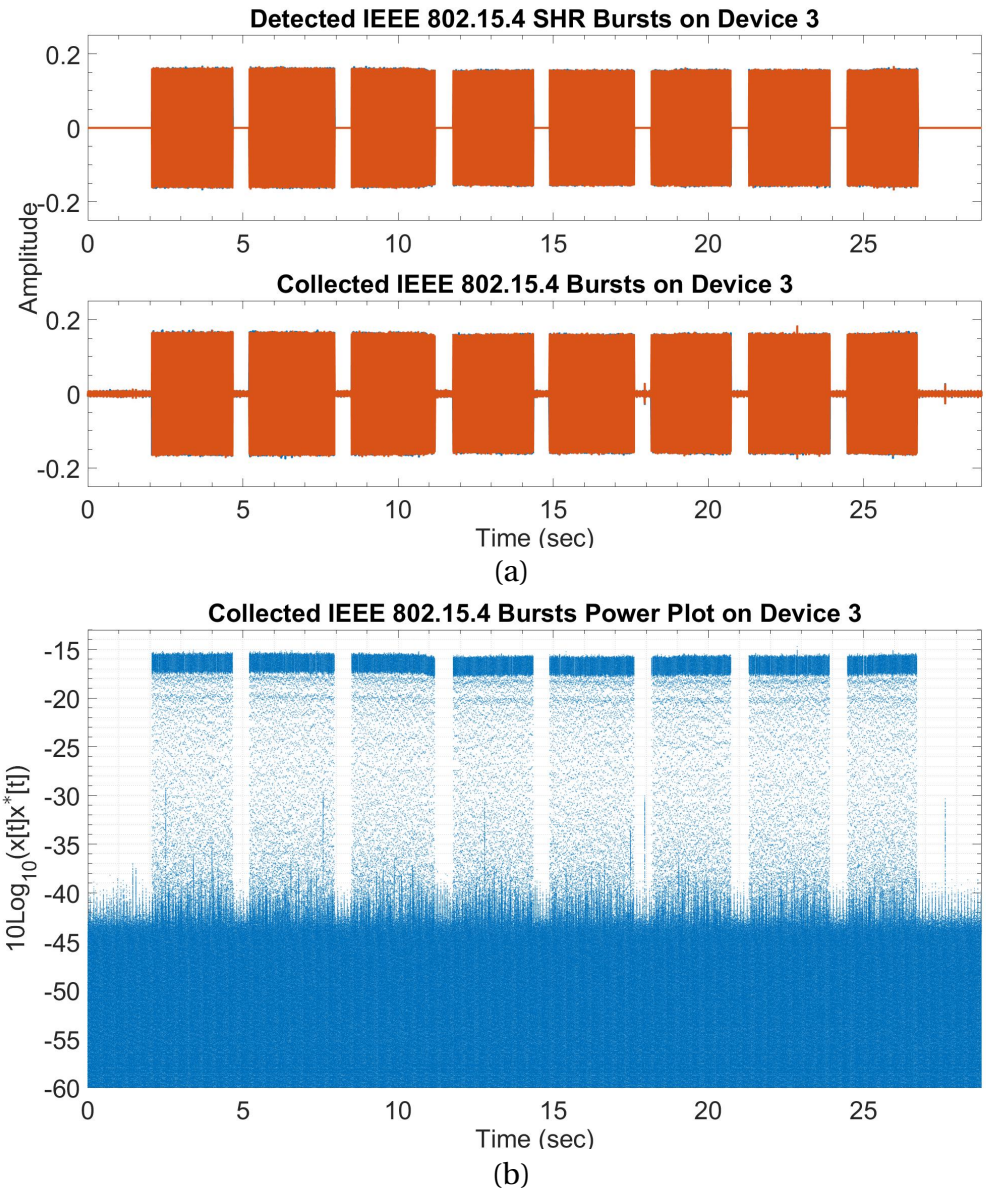
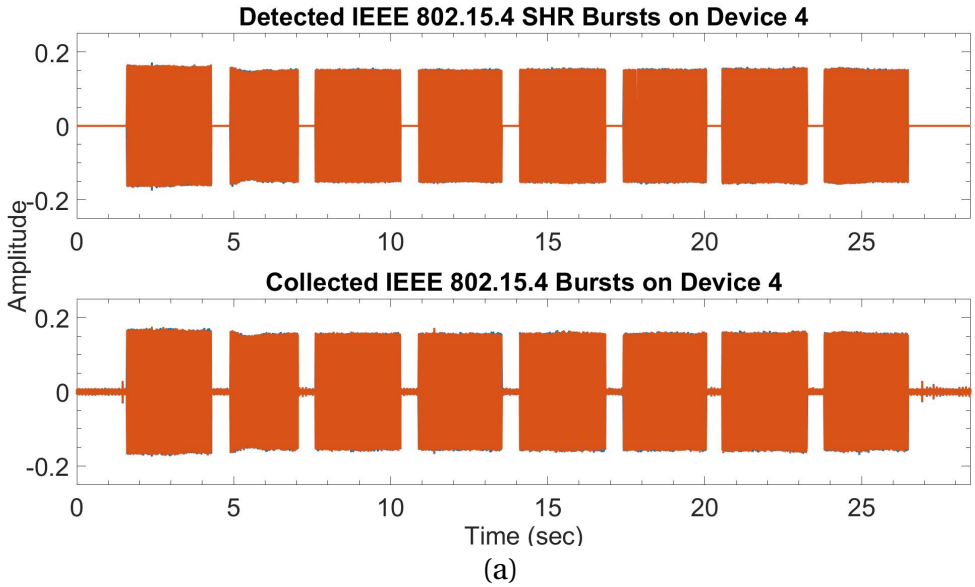
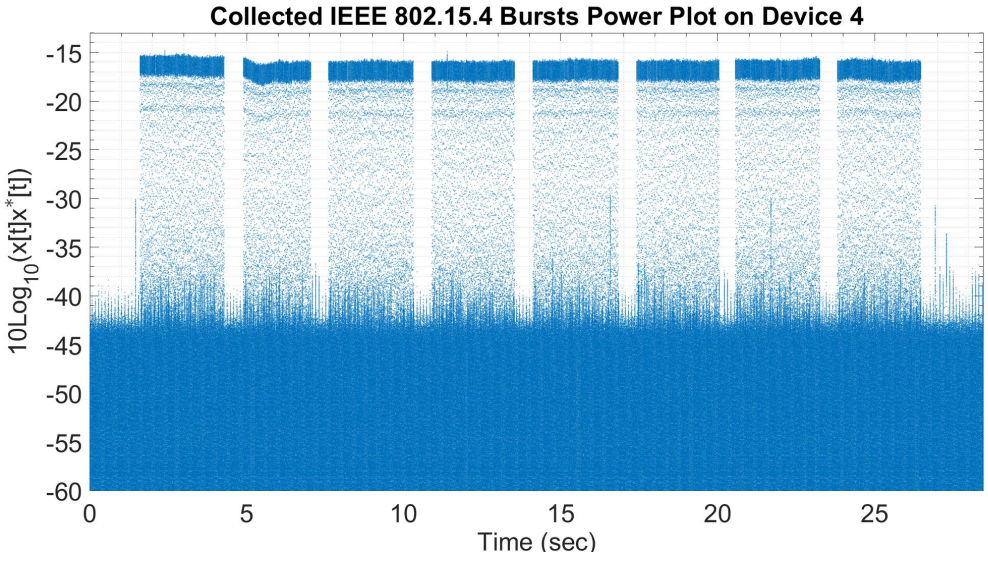


Figure A-14. (a) I/Q and (b) Power Plot on Device 3 of N_{Bursts} =1,912 bursts from Libpcap File Replayed 8-Times

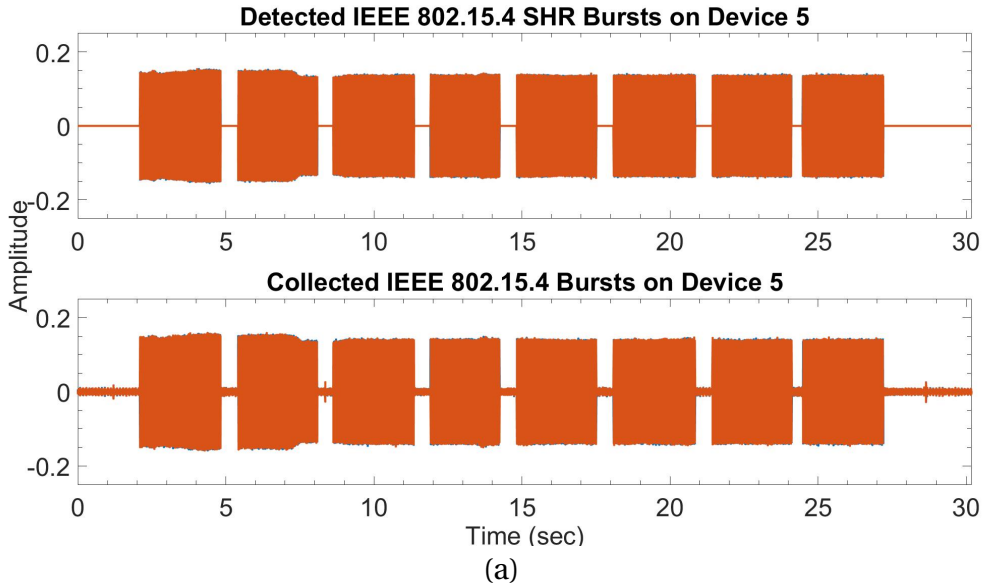


(a)

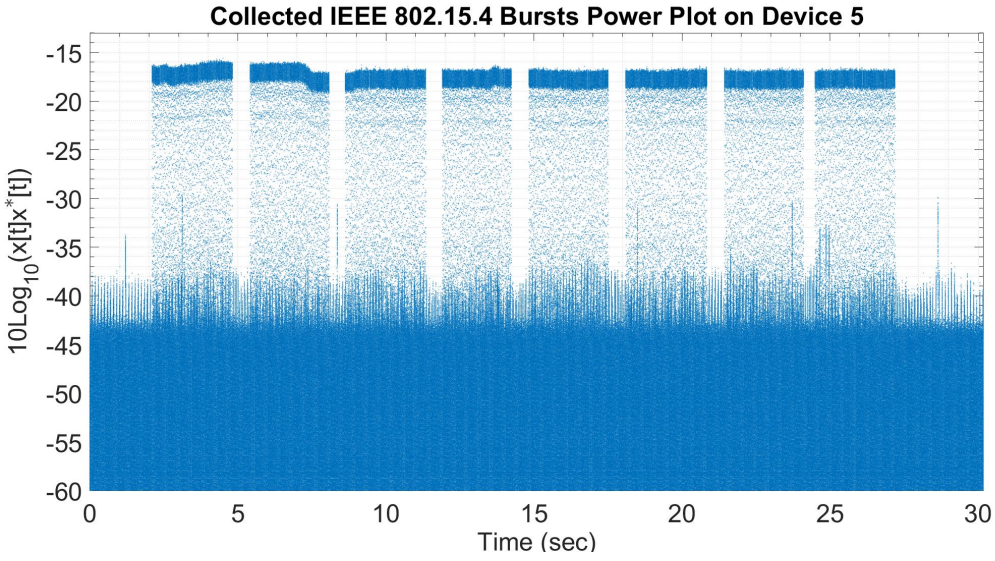


(b)

Figure A-15. (a) I/Q and (b) Power Plot on Device 4 of N_{Bursts} =1,912 bursts from Libpcap File Replayed 8-Times



(a)



(b)

Figure A-16. (a) I/Q and (b) Power Plot on Device 5 of N_{Bursts} =1,912 bursts from Libpcap File Replayed 8-Times

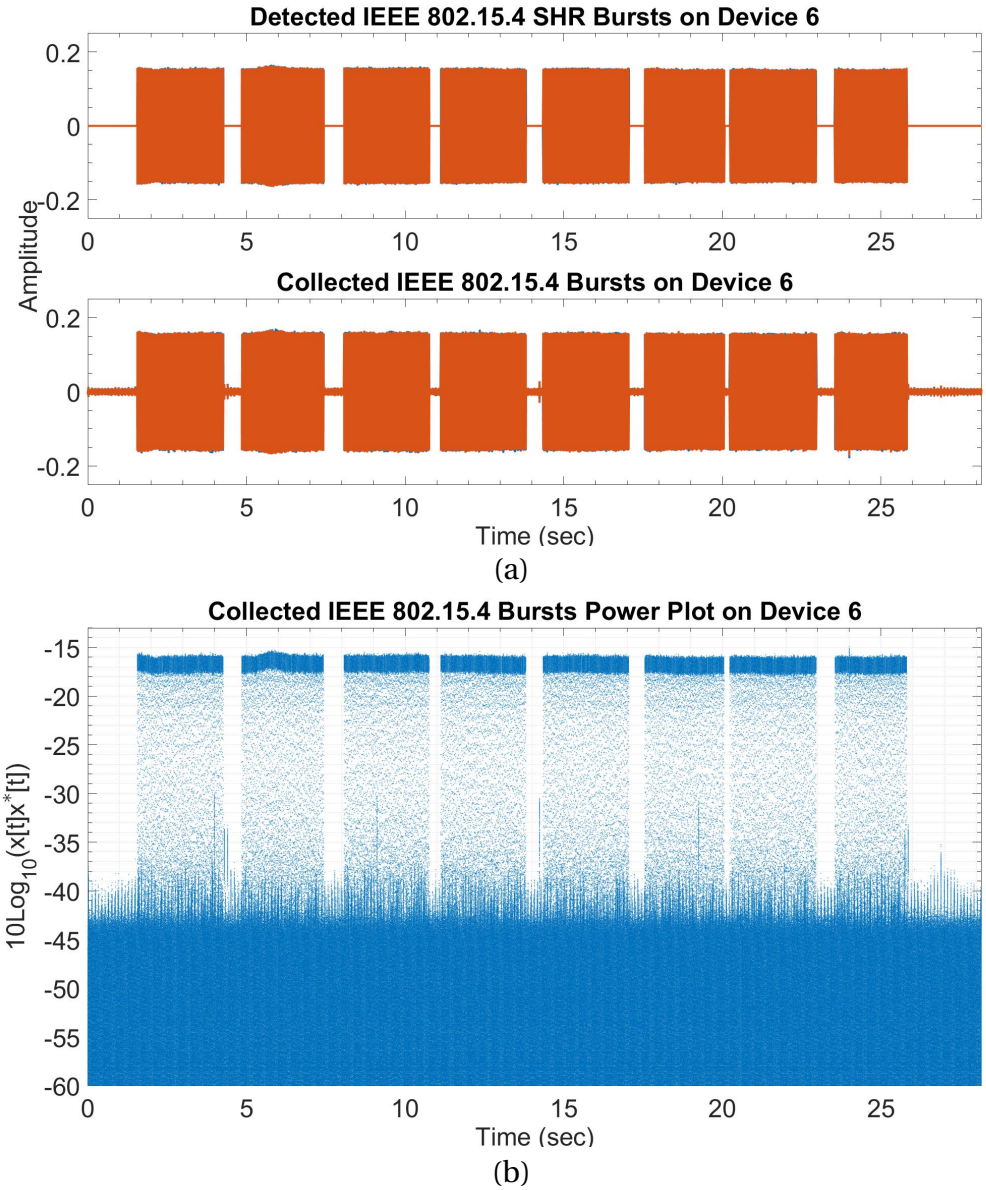
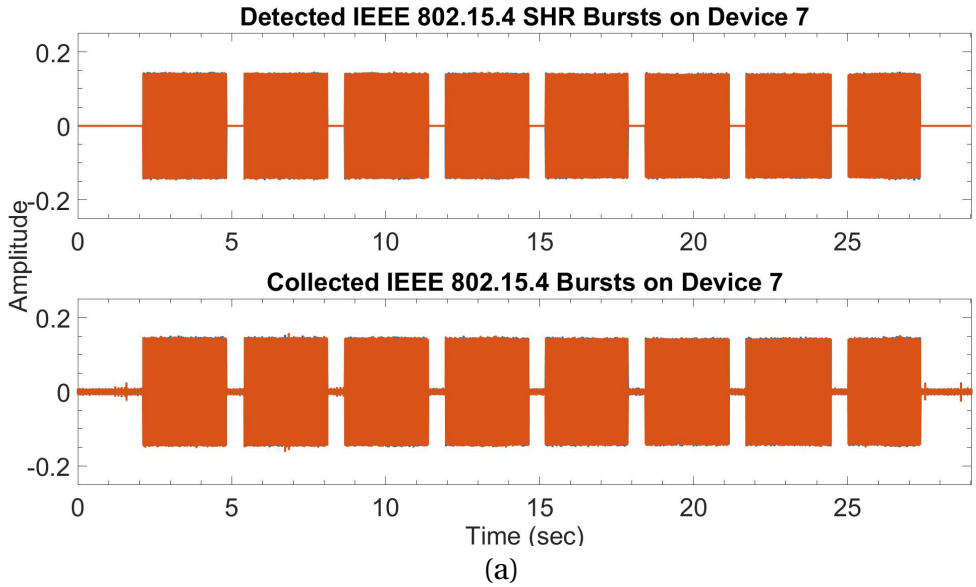
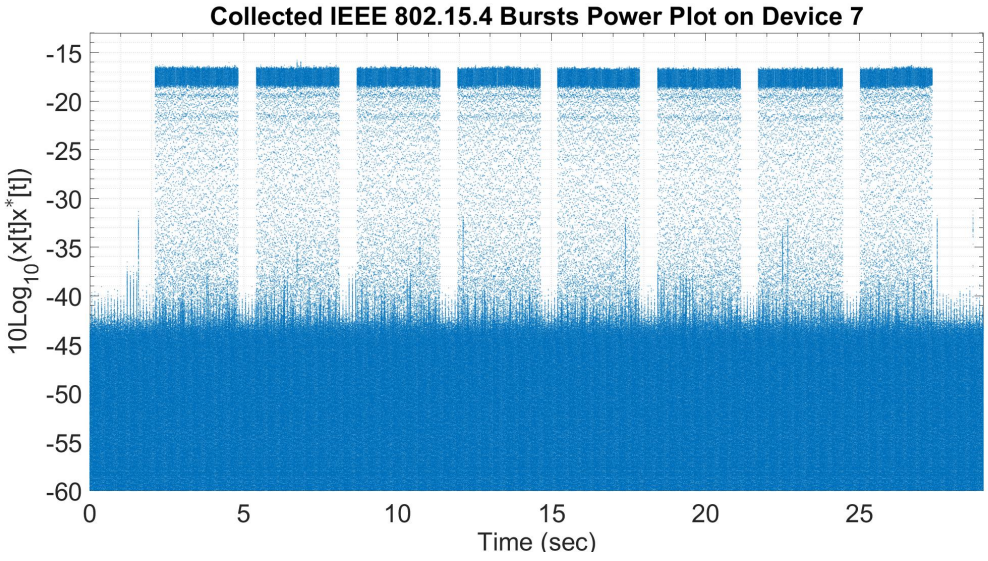


Figure A-17. (a) I/Q and (b) Power Plot on Device 6 of N_{Bursts} =1,912 bursts from Libpcap File Replayed 8-Times

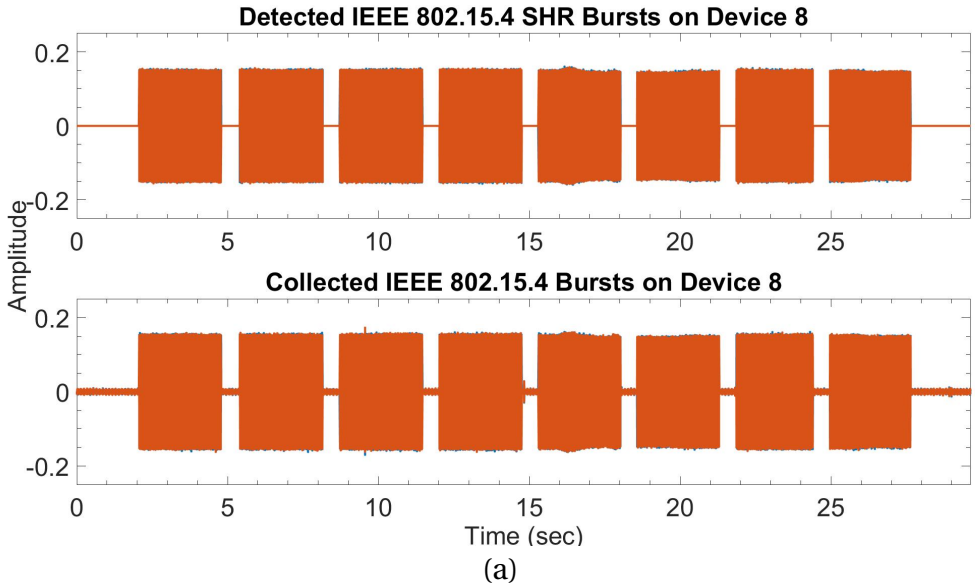


(a)

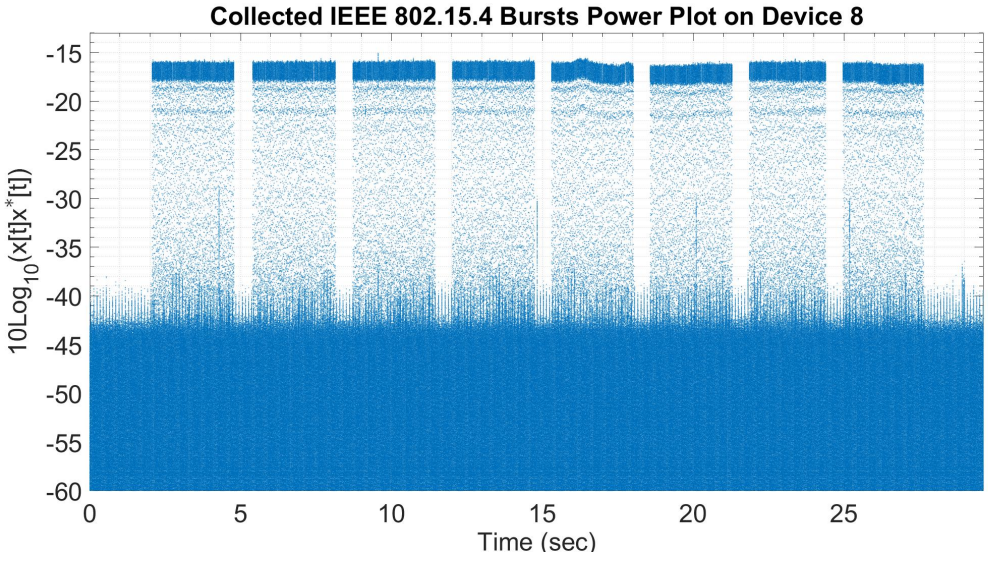


(b)

Figure A-18. (a) I/Q and (b) Power Plot on Device 7 of N_{Bursts} =1,912 bursts from Libpcap File Replayed 8-Times

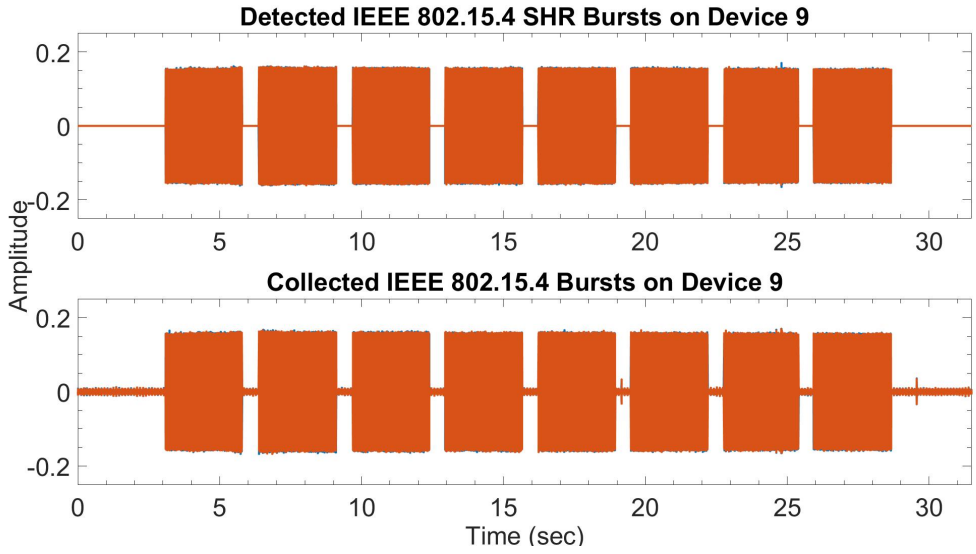


(a)

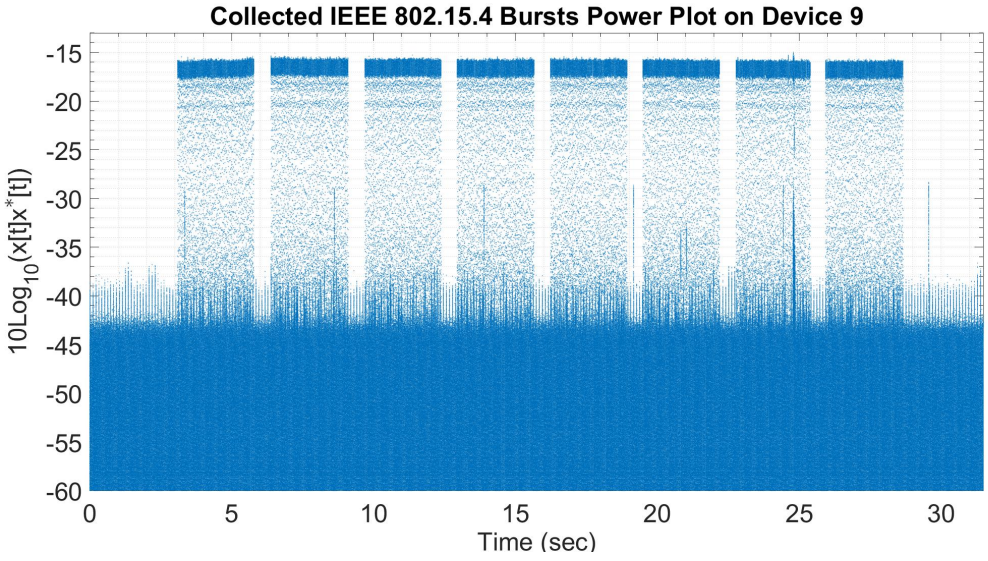


(b)

Figure A-19. (a) I/Q and (b) Power Plot on Device 8 of N_{Bursts} =1,912 bursts from Libpcap File Replayed 8-Times

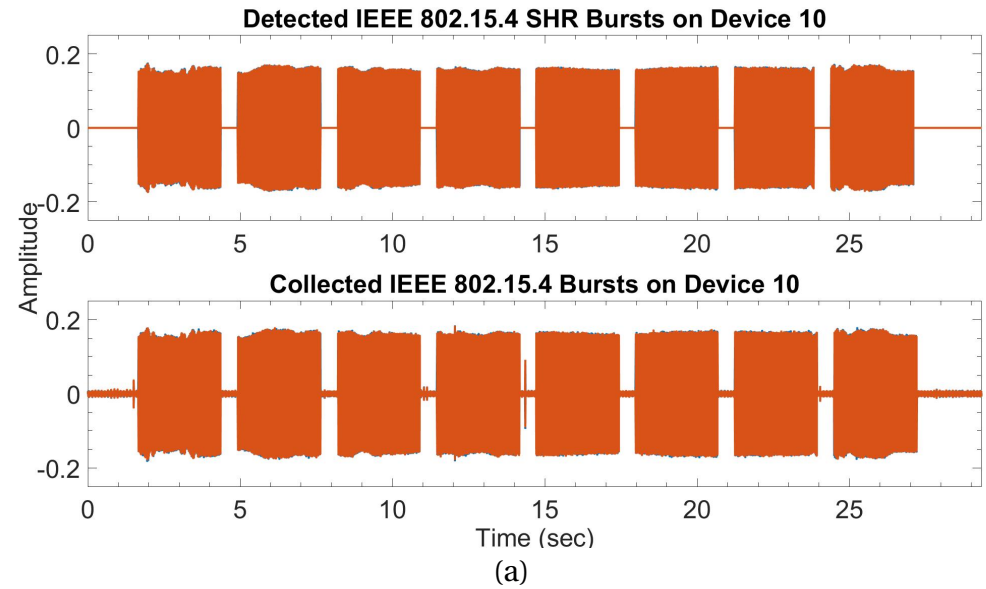


(a)

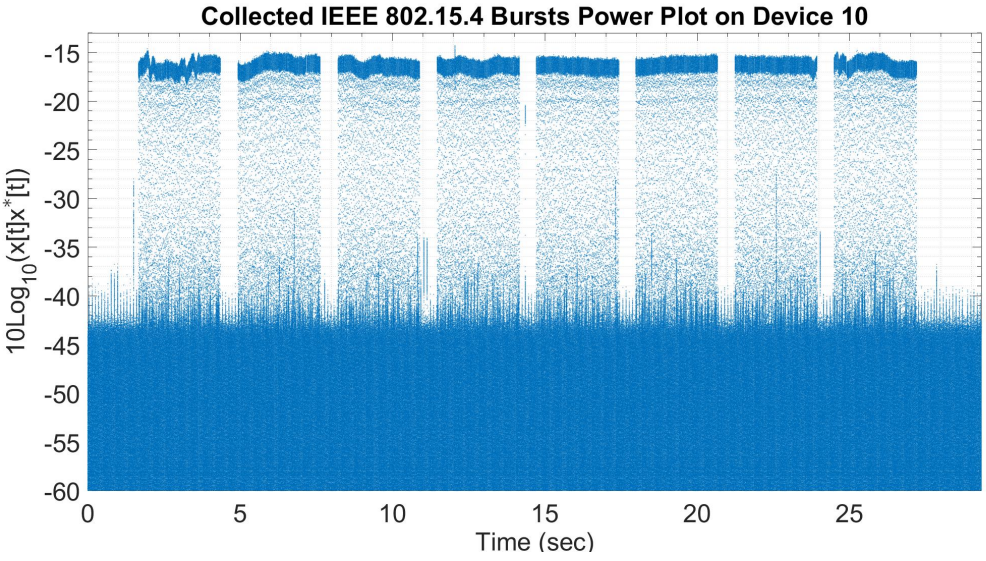


(b)

Figure A-20. (a) I/Q and (b) Power Plot on Device 9 of N_{Bursts} =1,912 bursts from Libpcap File Replayed 8-Times



(a)



(b)

Figure A-21. (a) I/Q and (b) Power Plot on Device 10 of N_{Bursts} =1,912 bursts from Libpcap File Replayed 8-Times

Appendix B. Device Collection Tables

Table 1. Collection Performance Tables for Devices 1 to 4

Device: 1

Time Span (sec)		25.7								
				Detected IEEE 802.15.4 Libpcap Data						
	Total Packets Transmitted	100.00%	1912				Packet Count	Average Val (B)	Min Val(B)	Max Val (B)
Preamble Sink Detected Bursts	Total Packets Detected	99.22%	1897	Packet Lengths	Total Packets	100.00%	1897	58.54	10	90
	Short Packets	0.00%	0		0-19	3.32%	63	12.32	10	18
	Bad CRC Packets	0.05%	1		20-39	2.53%	48	26.67	21	28
	Good CRC Packets	99.16%	1896		40-79	69.11%	1311	51.87	45	73
	Preambles Accepted	99.01%	1893		80-159	25.04%	475	86.28	80	90
	Preambles Rejected	0.21%	4							
	Total Processed Fingerprints	98.80%	1889		% Preamble's Fingerprinted	99.79%				

Device: 2

Time Span (sec)		25.548								
				Detected IEEE 802.15.4 Libpcap Data						
	Total Packets Transmitted	100.00%	1912				Packet Count	Average Val (B)	Min Val(B)	Max Val (B)
Preamble Sink Detected Bursts	Total Packets Detected	97.96%	1873	Packet Lengths	Total Packets	100.00%	1873	58.76	10	90
	Short Packets	0.00%	0		0-19	3.20%	60	12.23	10	18
	Bad CRC Packets	0.00%	0		20-39	2.24%	42	26.67	21	28
	Good CRC Packets	97.96%	1873		40-79	69.25%	1297	51.89	45	73
	Preambles Accepted	97.80%	1870		80-159	25.31%	474	86.27	80	90
	Preambles Rejected	0.16%	3							
	Total Processed Fingerprints	97.59%	1866		% Preamble's Fingerprinted	99.79%				

Device: 3

Time Span (sec)		25.89								
				Detected IEEE 802.15.4 Libpcap Data						
	Total Packets Transmitted	100.00%	1912				Packet Count	Average Val (B)	Min Val(B)	Max Val (B)
Preamble Sink Detected Bursts	Total Packets Detected	95.19%	1820	Packet Lengths	Total Packets	100.00%	1820	58.85	10	90
	Short Packets	0.00%	0		0-19	3.24%	59	12.24	10	18
	Bad CRC Packets	0.00%	0		20-39	2.47%	45	26.73	21	28
	Good CRC Packets	95.19%	1820		40-79	68.63%	1249	51.95	45	73
	Preambles Accepted	95.19%	1820		80-159	25.66%	467	86.28	80	90
	Preambles Rejected	0.00%	0							
	Total Processed Fingerprints	94.19%	1801		% Preamble's Fingerprinted	98.96%				

Device : 4

Time Span (sec)		25.758								
	Total Packets Transmitted	100.00%	1912				Packet Count	Average Val (B)	Min Val(B)	Max Val (B)
Preamble Sink Detected Bursts	Total Packets Detected	96.13%	1838	Packet Lengths	Total Packets	100.00%	1838	58.47	10	90
	Short Packets	0.00%	0		0-19	3.37%	62	12.16	10	18
	Bad CRC Packets	0.00%	0		20-39	2.50%	46	26.78	21	28
	Good CRC Packets	96.13%	1838		40-79	69.15%	1271	51.8	45	73
	Preambles Accepted	96.03%	1836		80-159	24.97%	459	86.37	80	90
	Preambles Rejected	0.10%	2							
	Total Processed Fingerprints	95.19%	1820		% Preamble's Fingerprinted	99.13%				

Table 2. Collection Performance Tables for Devices 5 to 8

Device: 5									
Time Span (sec)			25.71						
				Detected IEEE 802.15.4 Libpcap Data					
Total Packets Transmitted		100.00%	1912	Packet Lengths			Packet Count	Average Val (B)	Min Val(B)	Max Val (B)
Preamble Sink Detected Bursts	Total Packets Detected	97.75%	1869		Total Packets	100.00%	1869	58.51	1	90
	Short Packets	0.05%	1		0-19	3.42%	64	11.98	1	18
	Bad CRC Packets	0.00%	0		20-39	2.57%	48	26.67	21	28
	Good CRC Packets	97.70%	1868		40-79	68.81%	1286	51.84	45	73
	Preambles Accepted	97.65%	1867		80-159	25.20%	471	86.27	80	90
	Preambles Rejected	0.10%	2							
Total Processed Fingerprints		97.44%	1863	% Preamble's Fingerprinted		99.79%				

Device: 6									
Time Span (sec)			25.638						
				Detected IEEE 802.15.4 Libpcap Data					
Total Packets Transmitted		100.00%	1912	Packet Lengths			Packet Count	Average Val (B)	Min Val(B)	Max Val (B)
Preamble Sink Detected Bursts	Total Packets Detected	96.29%	1841		Total Packets	100.00%	1841	58.57	10	90
	Short Packets	0.00%	0		0-19	3.31%	61	12.26	10	18
	Bad CRC Packets	0.00%	0		20-39	2.61%	48	26.67	21	28
	Good CRC Packets	96.29%	1841		40-79	68.93%	1269	51.91	45	73
	Preambles Accepted	96.29%	1841		80-159	25.15%	463	86.22	80	90
	Preambles Rejected	0.00%	0							
Total Processed Fingerprints		95.50%	1826	% Preamble's Fingerprinted		99.19%				

Device: 7									
Time Span (sec)			25.665						
				Detected IEEE 802.15.4 Libpcap Data					
Total Packets Transmitted		100.00%	1912	Packet Lengths			Packet Count	Average Val (B)	Min Val(B)	Max Val (B)
Preamble Sink Detected Bursts	Total Packets Detected	98.27%	1879		Total Packets	100.00%	1879	58.46	10	90
	Short Packets	0.00%	0		0-19	3.35%	63	12.25	10	18
	Bad CRC Packets	0.00%	0		20-39	2.55%	48	26.67	21	28
	Good CRC Packets	98.27%	1879		40-79	69.19%	1300	51.89	45	73
	Preambles Accepted	98.27%	1879		80-159	24.91%	468	86.18	80	90
	Preambles Rejected	0.00%	0							
Total Processed Fingerprints		98.01%	1874	% Preamble's Fingerprinted		99.73%				

Device: 8									
Time Span (sec)			25.755						
				Detected IEEE 802.15.4 Libpcap Data					
Total Packets Transmitted		100.00%	1912	Packet Lengths			Packet Count	Average Val (B)	Min Val(B)	Max Val (B)
Preamble Sink Detected Bursts	Total Packets Detected	99.16%	1896		Total Packets	100.00%	1896	58.52	10	90
	Short Packets	0.00%	0		0-19	3.38%	64	12.25	10	18
	Bad CRC Packets	0.00%	0		20-39	2.53%	48	26.67	21	28
	Good CRC Packets	99.16%	1896		40-79	69.04%	1309	51.86	45	73
	Preambles Accepted	98.95%	1892		80-159	25.05%	475	86.33	80	90
	Preambles Rejected	0.21%	4							
Total Processed Fingerprints		98.90%	1891	% Preamble's Fingerprinted		99.95%				

Table 3. Collection Performance Tables for Devices 9 and 10

Device: 9										
Time Span (sec)			25.712							
				Detected IEEE 802.15.4 Libpcap Data						
Total Packets Transmitted		100.00%	1912	Packet Lengths			Packet Count	Average Val (B)	Min Val(B)	Max Val (B)
Preamble Sink Detected Bursts	Total Packets Detected	99.48%	1902		Total Packets	100.00%	1902	58.5	10	90
	Short Packets	0.00%	0		0-19	3.36%	64	12.25	10	18
	Bad CRC Packets	0.00%	0		20-39	2.52%	48	26.67	21	28
	Good CRC Packets	99.48%	1902		40-79	69.14%	1315	51.89	45	73
	Preambles Accepted	99.42%	1901		80-159	24.97%	475	86.23	80	90
	Preambles Rejected	0.05%	1							
Total Processed Fingerprints		99.37%	1900	% Preamble's Fingerprinted		99.95%				

Device: 10										
Time Span (sec)			25.534							
				Detected IEEE 802.15.4 Libpcap Data						
Total Packets Transmitted		100.00%	1912	Packet Lengths			Packet Count	Average Val (B)	Min Val(B)	Max Val (B)
Preamble Sink Detected Bursts	Total Packets Detected	99.90%	1910		Total Packets	100.00%	1910	58.54	10	90
	Short Packets	0.00%	0		0-19	3.35%	64	12.25	10	18
	Bad CRC Packets	0.00%	0		20-39	2.51%	48	26.67	21	28
	Good CRC Packets	99.90%	1910		40-79	69.06%	1319	51.87	45	73
	Preambles Accepted	99.84%	1909		80-159	25.08%	479	86.26	80	90
	Preambles Rejected	0.05%	1							
Total Processed Fingerprints		99.84%	1909	% Preamble's Fingerprinted		100.00%				

Table 4. Operational Performance Tables for Devices 1 to 4

Device: 1										
Time Span (sec)			25.166							
				Detected IEEE 802.15.4 Libpcap Data						
	Total Packets Transmitted	100.00%	1912	Packet Lengths			Packet Count	Average Val (B)	Min Val (B)	Max Val (B)
Preamble Sink Detected Bursts	Total Packets Detected	99.95%	1911		Total Packets	100.00%	1911	58.52	10	90
	Short Packets	0.00%	0		0-19	3.40%	65	12.32	10	18
	Bad CRC Packets	0.05%	1		20-39	2.51%	48	26.67	21	28
	Good CRC Packets	99.90%	1910		40-79	69.02%	1319	51.87	45	73
	Preambles Accepted	99.84%	1909		80-159	25.07%	479	86.27	80	90
	Preambles Rejected	0.10%	2							
	Total Processed Fingerprints	99.84%	1909		% Preamble's Fingerprinted	100.00%				

Device: 2										
Time Span (sec)			25.309							
				Detected IEEE 802.15.4 Libpcap Data						
	Total Packets Transmitted	100.00%	1912	Packet Lengths			Packet Count	Average Val (B)	Min Val (B)	Max Val (B)
Preamble Sink Detected Bursts	Total Packets Detected	100.05%	1913		Total Packets	100.00%	1913	58.52	1	90
	Short Packets	0.05%	1		0-19	3.40%	65	12.08	1	18
	Bad CRC Packets	0.00%	0		20-39	2.51%	48	26.67	21	28
	Good CRC Packets	100.00%	1912		40-79	69.00%	1320	51.87	45	73
	Preambles Accepted	99.90%	1910		80-159	25.09%	480	86.27	80	90
	Preambles Rejected	0.16%	3							
	Total Processed Fingerprints	99.90%	1910		% Preamble's Fingerprinted	100.00%				

Device: 3										
Time Span (sec)			25.215							
				Detected IEEE 802.15.4 Libpcap Data						
	Total Packets Transmitted	100.00%	1912	Packet Lengths			Packet Count	Average Val (B)	Min Val (B)	Max Val (B)
Preamble Sink Detected Bursts	Total Packets Detected	100.00%	1912		Total Packets	100.00%	1912	58.52	1	90
	Short Packets	0.05%	1		0-19	3.40%	65	12.08	1	18
	Bad CRC Packets	0.00%	0		20-39	2.51%	48	26.67	21	28
	Good CRC Packets	99.95%	1911		40-79	68.99%	1319	51.87	45	73
	Preambles Accepted	99.95%	1911		80-159	25.10%	480	86.27	80	90
	Preambles Rejected	0.05%	1							
	Total Processed Fingerprints	99.95%	1911		% Preamble's Fingerprinted	100.00%				

Device: 4										
Time Span (sec)			25.108							
				Detected IEEE 802.15.4 Libpcap Data						
	Total Packets Transmitted	100.00%	1912	Packet Lengths			Packet Count	Average Val (B)	Min Val (B)	Max Val (B)
Preamble Sink Detected Bursts	Total Packets Detected	99.95%	1911		Total Packets	100.00%	1911	58.57	10	90
	Short Packets	0.00%	0		0-19	3.30%	63	12.25	10	18
	Bad CRC Packets	0.00%	0		20-39	2.51%	48	26.67	21	28
	Good CRC Packets	99.95%	1911		40-79	69.07%	1320	51.87	45	73
	Preambles Accepted	99.79%	1908		80-159	25.12%	480	86.27	80	90
	Preambles Rejected	0.16%	3							
	Total Processed Fingerprints	99.79%	1908		% Preamble's Fingerprinted	100.00%				

Table 5. Operational Performance Tables for Devices 5 to 8

Device: 5

Time Span (sec)		25.262	
Total Packets Transmitted		100.00%	1912
Preamble Sink Detected Bursts	Total Packets Detected	100.00%	1912
	Short Packets	0.00%	0
	Bad CRC Packets	0.00%	0
	Good CRC Packets	100.00%	1912
	Preambles Accepted	100.00%	1912
	Preambles Rejected	0.00%	0
Total Processed Fingerprints		100.00%	1912

Detected IEEE 802.15.4 Libpcap Data

Packet Lengths			Packet Count	Average Val (B)	Min Val (B)	Max Val (B)
	Total Packets	100.00%	1912	58.55	10	90
	0-19	3.35%	64	12.25	10	18
	20-39	2.51%	48	26.67	21	28
	40-79	69.04%	1320	51.87	45	73
	80-159	25.10%	480	86.27	80	90
% Preamble's Fingerprinted		100.00%				

Device: 6

Time Span (sec)		25.201	
Total Packets Transmitted		100.00%	1912
Preamble Sink Detected Bursts	Total Packets Detected	99.95%	1911
	Short Packets	0.00%	0
	Bad CRC Packets	0.00%	0
	Good CRC Packets	99.95%	1911
	Preambles Accepted	99.84%	1909
	Preambles Rejected	0.10%	2
Total Processed Fingerprints		99.84%	1909

Detected IEEE 802.15.4 Libpcap Data

Packet Lengths			Packet Count	Average Val (B)	Min Val (B)	Max Val (B)
	Total Packets	100.00%	1911	58.57	10	90
	0-19	3.30%	63	12.25	10	18
	20-39	2.51%	48	26.67	21	28
	40-79	69.07%	1320	51.87	45	73
	80-159	25.12%	480	86.27	80	90
% Preamble's Fingerprinted		100.00%				

Device: 7

Time Span (sec)		25.186	
Total Packets Transmitted		100.00%	1912
Preamble Sink Detected Bursts	Total Packets Detected	100.00%	1912
	Short Packets	0.00%	0
	Bad CRC Packets	0.00%	0
	Good CRC Packets	100.00%	1912
	Preambles Accepted	99.95%	1911
	Preambles Rejected	0.05%	1
Total Processed Fingerprints		99.90%	1910

Detected IEEE 802.15.4 Libpcap Data

Packet Lengths			Packet Count	Average Val (B)	Min Val (B)	Max Val (B)
	Total Packets	100.00%	1912	58.55	10	90
	0-19	3.35%	64	12.25	10	18
	20-39	2.51%	48	26.67	21	28
	40-79	69.04%	1320	51.87	45	73
	80-159	25.10%	480	86.27	80	90
% Preamble's Fingerprinted		99.95%				

Device: 8

Time Span (sec)		25.112	
Total Packets Transmitted		100.00%	1912
Preamble Sink Detected Bursts	Total Packets Detected	100.05%	1913
	Short Packets	0.05%	1
	Bad CRC Packets	0.00%	0
	Good CRC Packets	100.00%	1912
	Preambles Accepted	100.00%	1912
	Preambles Rejected	0.05%	1
Total Processed Fingerprints		100.00%	1912

Detected IEEE 802.15.4 Libpcap Data

Packet Lengths			Packet Count	Average Val (B)	Min Val (B)	Max Val (B)
	Total Packets	100.00%	1913	58.52	1	90
	0-19	3.40%	65	12.08	1	18
	20-39	2.51%	48	26.67	21	28
	40-79	69.00%	1320	51.87	45	73
	80-159	25.09%	480	86.27	80	90
% Preamble's Fingerprinted		100.00%				

Table 6. Operational Performance Tables for Devices 9 and 10

Device: 9										
Time Span (sec)		25.182								
				Detected IEEE 802.15.4 Libpcap Data						
Total Packets Transmitted		100.00%	1912			Packet Count	Average Val (B)	Min Val (B)	Max Val (B)	
Preamble Sink Detected Bursts	Total Packets Detected	100.00%	1912	Packet Lengths	Total Packets	100.00%	1912	58.53	10	90
	Short Packets	0.00%	0		0-19	3.40%	65	12.32	10	18
	Bad CRC Packets	0.05%	1		20-39	2.51%	48	26.67	21	28
	Good CRC Packets	99.95%	1911		40-79	68.99%	1319	51.88	45	73
	Preambles Accepted	99.95%	1911		80-159	25.10%	480	86.27	80	90
	Preambles Rejected	0.05%	1							
Total Processed Fingerprints		99.84%	1909		% Preamble's Fingerprinted	99.90%				

Device: 10										
Time Span (sec)		25.217								
				Detected IEEE 802.15.4 Libpcap Data						
Total Packets Transmitted		100.00%	1912			Packet Count	Average Val (B)	Min Val (B)	Max Val (B)	
Preamble Sink Detected Bursts	Total Packets Detected	99.95%	1911	Packet Lengths	Total Packets	100.00%	1911	58.53	1	90
	Short Packets	0.05%	1		0-19	3.40%	65	12.08	1	18
	Bad CRC Packets	0.00%	0		20-39	2.51%	48	26.67	21	28
	Good CRC Packets	99.90%	1910		40-79	68.97%	1318	51.88	45	73
	Preambles Accepted	99.90%	1910		80-159	25.12%	480	86.27	80	90
	Preambles Rejected	0.05%	1							
Total Processed Fingerprints		99.74%	1907		% Preamble's Fingerprinted	99.84%				

Table 7. Operational NRT Device Discrimination Joint PMF CM for N_d =10 Devices

RF-DNA PMF	Classified Device											Input Device Totals
	Device	1	2	3	4	5	6	7	8	9	10	
Input Device	1	8.24%	0.00%	0.00%	1.75%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	10.00%
	2	0.06%	9.69%	0.00%	0.00%	0.04%	0.00%	0.00%	0.00%	0.00%	0.21%	10.00%
	3	0.00%	0.00%	10.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.00%	0.00%	10.01%
	4	0.00%	0.00%	0.00%	9.99%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	9.99%
	5	0.51%	0.01%	0.00%	0.00%	9.50%	0.00%	0.00%	0.00%	0.00%	0.00%	10.01%
	6	0.00%	0.00%	0.00%	0.00%	0.00%	9.84%	0.01%	0.00%	0.05%	0.10%	10.00%
	7	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	9.87%	0.00%	0.13%	0.00%	10.00%
	8	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	10.01%	0.00%	0.00%	10.01%
	9	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.05%	0.01%	9.94%	0.00%	10.00%
	10	0.00%	0.00%	0.00%	0.00%	0.00%	0.14%	0.00%	0.00%	0.01%	9.84%	9.99%
Classified Device Totals		8.81%	9.69%	10.00%	11.75%	9.54%	9.99%	9.92%	10.02%	10.13%	10.15%	100.00%

Appendix C. Statistical File Examples

The three files below contain an example of the statistical data collected on Device 10 during the operational performance evaluation. The file's were limited to four-bursts due to the amount of data contained in each text file.

C.1 preamble_sink Statistical File Example

```
1
2  ================================================================
3  Collection started on 2019-01-12_17:58:11
4  Buffer size set to  4
5  Sample Rate at 4e+06 Samp/sec
6  Preamble sample length at 4e+06 Samp/sec is 640
7  Packet sample length at 4e+06 Samp/sec is 17024
8  ================================================================
9
10 ================================================================
11 Current Burst Sample Length: 2044
12 Buffer + Detected Burst Sample length: 12264
13 Total Packets Detected: 1
14 Short Packets: 0
15 Bad CRC Packets: 0
16 Good CRC Packets: 1
17 Total Preambles Processed
18 of 1 Total Packets Detected: 1
19 Preambles Accepted: 1
20 Preambles Rejected: 0
21 ================================================================
22
23 ================================================================
24 Current Burst Sample Length: 2044
25 Buffer + Detected Burst Sample length: 12264
26 Total Packets Detected: 2
27 Short Packets: 0
28 Bad CRC Packets: 0
29 Good CRC Packets: 2
30 Total Preambles Processed
31 of 2 Total Packets Detected: 2
32 Preambles Accepted: 2
33 Preambles Rejected: 0
34 ================================================================
35 ...
36 ...
37 ...
38 ...
39 ================================================================
40 Current Burst Sample Length: 2044
41 Buffer + Detected Burst Sample length: 12264
```

```
Total Packets Detected: 1910
Short Packets: 1
Bad CRC Packets: 0
Good CRC Packets: 1909
Total Preambles Processed
of 1910 Total Packets Detected: 1910
Preambles Accepted: 1909
Preambles Rejected: 1
================================================================================


================================================================================
Current Burst Sample Length: 2044
Buffer + Detected Burst Sample length: 12264
Total Packets Detected: 1911
Short Packets: 1
Bad CRC Packets: 0
Good CRC Packets: 1910
Total Preambles Processed
of 1911 Total Packets Detected: 1911
Preambles Accepted: 1910
Preambles Rejected: 1
================================================================================
```

C.2 Dna_detector_ccf Device Statistical File Example

```

================================================================================
Collection started on 2019-01-12_17:58:11
Sample Rate at 4e+06
Preamble sample length at 4e+06 Samp/sec is 640
Packet sample length at 4e+06 Samp/sec is 17024
================================================================================


--------------------------------------------------------------------------------
Burst: 1
Device Most Likely: 10
Device Result Value: 1.193546
Total Valid Fingerprints: 1
Total Invalid Fingerprints: 0
Emitter_1 Count:0    Emitter_2 Count:0    Emitter_3 Count:0    Emitter_4 Count:0    Emitter_5 Count:0    Emitter_6 Count:0
      Emitter_7 Count:0    Emitter_8 Count:0    Emitter_9 Count:0    Emitter_10 Count:1
--------------------------------------------------------------------------------


--------------------------------------------------------------------------------
Burst: 2
Device Most Likely: 10
Device Result Value: 0.836388
Total Valid Fingerprints: 2
Total Invalid Fingerprints: 0
Emitter_1 Count:0    Emitter_2 Count:0    Emitter_3 Count:0    Emitter_4 Count:0    Emitter_5 Count:0    Emitter_6 Count:0
      Emitter_7 Count:0    Emitter_8 Count:0    Emitter_9 Count:0    Emitter_10 Count:2
```

```
25 ------------------------------------------------------------------------------
26 ...
27 ...
28 ...
29 ...
30 ------------------------------------------------------------------------------
31 Burst: 1906
32 Device Most Likely: 10
33 Device Result Value: 1.017697
34 Total Valid Fingerprints: 1906
35 Total Invalid Fingerprints: 0
36 Emitter_1 Count:0    Emitter_2 Count:0    Emitter_3 Count:0    Emitter_4 Count:0    Emitter_5 Count:0    Emitter_6 Count:27
       Emitter_7 Count:0    Emitter_8 Count:0    Emitter_9 Count:1    Emitter_10 Count:1878
37 ------------------------------------------------------------------------------
38
39 ------------------------------------------------------------------------------
40 Burst: 1907
41 Device Most Likely: 10
42 Device Result Value: 0.799719
43 Total Valid Fingerprints: 1907
44 Total Invalid Fingerprints: 0
45 Emitter_1 Count:0    Emitter_2 Count:0    Emitter_3 Count:0    Emitter_4 Count:0    Emitter_5 Count:0    Emitter_6 Count:27
       Emitter_7 Count:0    Emitter_8 Count:0    Emitter_9 Count:1    Emitter_10 Count:1879
46 ------------------------------------------------------------------------------
```

C.3 Dna_detector_ccf Fingerprint Statistical File Example

```
1
2 ==============================================================================
3 Collection started on 2019-01-12_17:58:11
4 Sample Rate at 4e+06
5
6 Preamble sample length at 4e+06 Samp/sec is 640
7 Packet sample length at 4e+06 Samp/sec is 17024
8 Loaded Classification Matrix Dimensions: 90 by 9
9   -0.0179987   -0.0138279    0.0492875  -0.00519748    0.281197    0.166237  -0.0371916    0.108293   0.00584679
10   0.0519962   -0.0650138    0.0100148    0.092154   -0.133937    0.253971   0.0965857    0.206419    0.220455
11   0.0650591    -0.104349   -0.0112158    0.106646    0.178953    0.191529    0.169982    0.223511    0.123336
12    0.315404    -0.804263    0.557634   0.0858229    0.375554   -0.137245    0.165134   -0.192862  -0.0521735
13   0.0539755    -0.110696   0.0015731   -0.502993    0.413656    0.636204   -0.773287  -0.0236586    0.607816
14    0.205591     0.224312    0.601665   -0.664338    0.327243    0.352247    0.184607 -0.00797385    0.243865
15  -0.0288187     0.162438   -0.263308    0.128726    0.157559  -0.0410198   0.0192086  -0.0959234    0.201986
16  -0.00331162   0.00513426   0.0195337 -0.00185531   0.00113047 -0.00632859   0.0136545   0.00765422 -0.00407964
17   0.0122842   -0.0694236    0.151027   -0.0556066  -0.0619126   0.0200212   0.0101293    0.050921  -0.0970899
18  -0.00116661   0.00804955   0.00223123  0.00823627  -0.0051349   -0.010797   0.0226886   -0.007041 -0.000770946
19   0.00141869   0.00136686   0.00194486  0.00390335   0.00644027      0.0049   0.00280831  -0.0119721 -0.00876289
20  0.000303979 -0.00228553    -0.012385   0.00611358 -0.00362197   0.00808109   0.00849944   0.00209835   0.00443739
21    0.286092     0.142002   -0.0846356  -0.0348339  -0.0314808   -0.110885  -0.00964886  -0.00242085  -0.0020572
22   0.0601666   -0.0552247   0.0268359   0.0590591    -0.02967   -0.106003 -0.000755145   -0.0580027    0.180717
23    0.222119   -0.0793704   -0.0165477    0.105181   -0.214649  -0.0423035   -0.111313   0.0681685   0.0817924
24  -0.0640838     0.112785   0.0457627   0.0215456   0.0424662 -0.00647726 -0.00585118 -0.00699142  0.00176661
```

25	0.00662764	−0.0130145	0.00913062	−0.00687832	−0.00758337	−0.00270296	−0.00389443	0.0169814	−0.0098258
26	0.0467916	−0.0791779	−0.010964	−0.0188642	−0.0355097	−0.00243888	0.0025443	0.0285843	−0.020987
27	−0.0139836	0.00224475	−0.000782094	0.0106473	0.0162947	−0.00468398	0.0170125	−0.000588703	−0.00173349
28	0.00135554	−0.00194579	0.00212064	−0.0018191	0.0174199	0.00213627	0.00131997	0.00053738	−0.00648701
29	0.006105	−0.00286979	0.00289305	0.00144902	0.00308971	−0.00172469	0.00372499	0.017194	−0.0023469
30	0.26679	0.13497	−0.0396221	−0.057125	0.0106326	−0.0174177	−0.0544295	0.189978	−0.10586
31	0.00702072	−0.0815799	0.0622956	0.0856106	−0.0553958	−0.160043	0.0644781	0.314954	−0.0852966
32	0.150562	−0.087497	0.0628471	0.110113	−0.0482736	−0.117914	−0.076226	0.204006	0.0174335
33	−0.0308837	0.0869382	0.0328359	0.0330014	0.0902179	−0.00517578	−0.0378798	−0.0905071	0.0464061
34	0.00485134	−0.00929916	0.00463606	−0.000319247	−0.000540768	0.00334702	−0.00240521	0.00700152	−0.00905908
35	0.0273823	−0.0562473	−0.0563315	−0.00707477	−0.0396406	0.0127766	0.0301294	0.0619016	0.00743245
36	0.00246855	0.0159585	0.00940016	0.00335823	−0.0222815	0.0153068	0.025499	−0.00229938	0.0106375
37	−0.00239028	−0.00152254	−0.0117177	0.00200379	0.00888086	0.00303322	0.00102708	−0.0122456	−0.0141718
38	0.000811983	0.00226911	0.0094978	−0.000587597	0.0064853	0.00228381	0.00781912	−0.011869	−0.0047277
39	0.270512	0.135969	−0.0894139	−0.0291822	0.0363417	−0.0140701	−0.097259	−0.000771328	0.126223
40	0.0700662	−0.0159998	0.0571228	0.0690439	0.070612	−0.136603	0.067192	0.0170464	0.121596
41	0.192584	−0.0612598	0.07531	0.0810668	−0.0239006	−0.120201	−0.0909007	0.0886095	0.0738793
42	−0.0440164	0.071479	0.0846799	−0.00196105	0.00153133	−0.0129619	−0.0358571	−0.0187779	−0.0511077
43	0.00015605	−0.00464072	0.00819676	−0.00194985	−0.00267484	−0.00492951	0.00089783	0.00487488	0.00335984
44	0.0371283	−0.0568256	−0.069413	−0.000454897	−0.013599	0.00491682	0.0295402	0.0305295	0.0380307
45	−0.0105563	0.0060682	0.0123607	−0.0047119	0.0322205	−0.00164861	0.00630031	0.0073825	0.053492
46	−0.00193289	−0.00316073	−0.010652	0.005202	0.00458249	−0.00503012	−0.00577202	0.0168298	−0.0334098
47	1.48892e−05	−0.00669837	−0.00543729	−0.0042167	0.00630061	−0.00349612	−0.0103318	0.00553268	−0.000708032
48	0.240667	0.140633	−0.0231852	−0.0583104	−0.00973171	−0.0220327	−0.0138669	0.0804568	0.0761459
49	0.0239535	−0.0094095	0.0184948	0.0529527	0.141669	−0.162518	0.00136283	0.213032	0.191085
50	0.158215	−0.0575029	−0.111884	0.0716962	0.0967758	−0.173811	−0.101035	0.102195	0.182563
51	−0.0360789	0.077554	0.0788549	0.0111567	0.0915742	0.00938974	−0.0511118	−0.0515102	−0.0885251
52	−0.0017018	0.0015205	−0.0125357	0.00628536	0.00468503	−0.00530977	0.00116916	0.00378986	0.00727305
53	0.027629	−0.0594598	−0.0626026	−0.0065738	−0.0565151	−0.00730848	0.0359538	0.0486606	0.0644957
54	−0.000883298	0.0168459	0.0213659	−0.00601562	−0.00753495	0.0097391	−0.00421009	0.0103229	0.00841235
55	0.00551755	−0.00206573	−0.010558	0.00683553	0.0119927	0.0116338	0.0252045	−0.00351846	0.0224415
56	−0.000548334	−0.00396358	−0.0169977	0.00132838	0.0194445	−0.00063864	−0.0159161	−0.0106031	−0.0231037
57	0.220396	0.091192	−0.0901883	−0.0576103	−0.0433209	0.015877	−0.0996187	−0.0176815	0.194714
58	0.0326252	−0.0232445	0.0394201	0.0357308	0.0381709	−0.188134	−0.0077281	−0.0231976	0.0818933
59	0.195014	−0.0277167	−0.0183819	0.0916202	−0.0363662	−0.0526228	−0.205489	0.117058	−0.128334
60	−0.0304532	0.0706435	0.0785722	0.0159118	0.00751659	−0.0258178	−0.0277924	−0.0397856	0.0293018
61	0.000664844	0.000426695	−0.0120476	0.00667781	0.00561718	−0.00373585	0.00695089	0.00737165	0.0101539
62	0.0230686	−0.0432014	−0.0807095	−0.00363105	−0.00217805	0.0186467	0.0242959	0.0482847	0.0167243
63	−0.00518571	0.0104006	0.00164055	0.00504683	0.0235527	0.00532678	−0.0182492	−0.00432308	−0.0813744
64	0.00678387	−0.0101755	−0.000806586	0.00106888	0.00129832	0.012935	0.0327275	−0.0132255	0.0507408
65	0.00352698	−0.00639224	−0.00184754	−0.00200365	−0.0128195	0.011643	−0.00362152	−0.0224655	−0.0207719
66	0.263343	0.141425	−0.0185347	0.00940641	−0.00292029	0.023133	0.0143007	0.0942048	−0.00535658
67	−0.00394384	0.00353918	0.0248182	0.0055025	0.108469	−0.212352	−0.0504097	0.244767	−0.132579
68	0.154494	−0.017042	−0.0236012	0.0803724	0.0651184	−0.154514	−0.154937	0.0948392	−0.0341468
69	−0.0305	0.0436751	0.0646544	0.00291418	0.0690874	0.0260546	−0.0436364	−0.0356784	−0.0720672
70	0.000889159	0.000546561	−0.019191	0.00373607	−0.00234838	−0.0106462	−0.00191432	−0.00159631	0.0190787
71	0.0268579	−0.0344389	−0.0665503	0.00481281	−0.0558736	−0.0153351	0.0394623	0.0122939	0.0605611
72	−0.00273179	0.00969519	−3.53648e−05	0.00289651	0.0169789	−0.00535893	−0.0264398	−0.0343602	−0.0579403
73	0.0021705	0.00530617	−0.00371545	0.0107177	−0.0161151	0.0103277	0.0611815	0.0241568	0.013393
74	0.000575686	−0.00387589	−0.000264265	0.00456252	0.00632049	0.000761766	0.0102303	−0.00407106	−0.0116216
75	0.264313	0.0901443	−0.0999181	0.0726945	−0.125024	0.0621761	0.0548034	0.0817263	−0.0235207
76	−0.0222946	0.00601534	0.176647	0.196407	−0.0600623	−0.05713	0.315419	0.283528	−0.0445553
77	0.152544	0.0400634	0.184454	0.204482	−0.0491684	0.00177651	0.120559	0.174118	0.223844
78	−0.0236855	0.0607816	0.0519161	−0.00763007	−0.00999048	−0.0530825	−0.0590816	0.109305	−0.0587402

```
 0.00163791  −0.00182925   0.00773689  −0.00100184   0.00115462  −0.00284512   0.00359856   0.00317279   0.000331348
 0.010655    −0.0416392   −0.037304    0.00823299   0.014264     0.034567     0.0447979   −0.0692184    0.0569477
 0.0110828    0.000542419 −0.0251615   0.0172514   −0.0223341    0.0279769    0.034671    −0.0281312   −0.0349511
−0.00451187   0.000598738 −0.00574578  −0.0034096   −0.0060025    0.000944656 −0.0376179   −0.0286255   −0.0613489
−0.00418865   0.00350385   0.0130416   −0.00248068  −0.00689904   −0.0054856    0.00642524  −0.00279389   0.0285479
 0.351167     0.133245     0.0211305    0.292858    −0.470838     0.170856     0.107673    −0.554021    −0.267231
−0.0277754    0.00332057  −0.0596565   −0.0333592    0.122579    −0.0798377   −0.0312913    0.0319849    0.0233509
−0.0489184   −0.0156965   −0.0383189   −0.0130023    0.0934613   −0.0143486    0.019117    −0.109788     0.021779
 0.0134799    0.0830591    0.139502     0.0166282   −0.00263858   0.0576215   −0.022693    −0.0928801    0.02145
−0.00119037  −0.00438005  −0.0119757   −0.00144486   0.00168315   0.00160842   0.00400101   0.00191221   0.00738228
−0.0111678   −0.0619892   −0.0966585   −0.0105575    0.00696647  −0.0310652    0.0264452    0.050225    −0.023025
 0.00979592   0.00639145  −0.00898956   0.0124372   −0.015967     0.0120717   −0.0142736    0.0251983   −0.0872037
−0.0106373    0.0208767    0.0265617    0.00340747   0.00472755   0.00884205  −0.0415524   −0.0257788    0.0317484
−0.00248773  −0.000859742  0.00147527   0.000971058 −0.0295901   −0.00519992   0.0059612    0.0141136   −0.00987076
−0.0102819   −0.00200367   0.0133442   −0.00706274   0.015592    −0.00743293  −0.00384492   0.0181613    0.0181075
−0.00973775  −0.00370472   0.0112811   −0.00745067   0.0120673   −0.00657913  −0.00270948   0.0114451    0.0290378
 0.00307149   0.00607471   0.00343391   0.00515173   0.00215804  −0.00903676  −0.00271573   0.00654477   0.0228145
−0.000742659  0.0428133    0.059984     0.00770555   0.0519115   −0.0231534    0.00277199   0.00406197   0.0590788
 0.00513118   0.00392664   0.00314689   0.00428373  −0.00747823  −0.0040994    0.00397393  −0.0162887   −0.0158522
 0.00383221  −0.0328871   −0.0266809   −0.00737345  −0.0574029    0.0313202    0.00279902  −0.0172337   −0.058471

═══════════════════════════════════════════════════════════════════════════

Loaded Means Matrix Dimensions: 10 by 9
 0.735917   −0.220484    0.397417   −0.169663    0.0318169   −0.103576   −0.126829    0.164935   −0.0316259
 0.0508788  −0.966638    0.854638    0.216482   −0.241939     0.0732671   0.025962   −0.0406058    0.0204084
 5.06297     0.238439   −0.407196    0.123757   −0.113997     0.0384649   0.100577    0.0214466   −0.0375498
 1.15775     0.160057    0.0491624  −0.125593    0.19858      0.0499035  −0.281216   −0.122833    −0.069233
 0.101127   −0.866081   −0.104861   −0.189655   −0.0845013   −0.278503    0.150856   −0.076027     0.0622165
−2.14498    −0.998712   −0.248582   −0.129318    0.0220415    0.199162    0.16485     0.0138251   −0.136249
−2.25908     0.990961   −0.376559    0.0520503  −0.56899     −0.0317732  −0.129809    0.00742225  −0.00259504
−0.487356    2.23551     0.365867   −0.0948389   0.161246     0.0659613   0.174637   −0.0125971    0.0448772
−1.78553     0.114444   −0.180992    0.308321    0.411908    −0.169985   −0.00329653  0.0136882   −0.0551149
−0.431695   −0.687494   −0.348894    0.00845715  0.183836     0.157079   −0.0757309   0.0307465    0.204865

═══════════════════════════════════════════════════════════════════════════

Loaded Normalization Vector Dimensions: 1 by 90
    13704.5     12.9373     2.04432    0.516744     8.52435     5.36929 7.41251e−13     5.17069     2.05593      307300
    4.18024     2.29354    0.513156      12.445      8.2912 1.11898e−12     4.26269     1.41332      300307     4.28693
    2.29232    0.513107      12.647      8.54486 1.13372e−12     4.37296      1.4717      296657     4.48851
    2.33211    0.510407      12.5228     8.4741 1.15082e−12     4.36407     1.48042      294089     4.26038     2.32718
   0.511454     12.4578     8.44662 1.14888e−12     4.33983     1.46938      285441     4.18313     2.32924
   0.512439     12.5217     8.3969 1.15273e−12     4.34458     1.46239      293789     4.23062     2.30567     0.51427
    12.6243     8.50782 1.1198e−12     4.30189     1.45054      295718     4.27182     2.61244    0.626118
    11.7778     6.28912 1.1261e−12     4.02128     1.43511      303840     4.86541     3.02887    0.401845     41.5998
    19.5941 1.07547e−12     3.98964     1.34588      356727     3.20272     2.59439      0.6481      4.3408
    5.69092 1.15874e−12     3.69243     1.54401

═══════════════════════════════════════════════════════════════════════════

Loaded X−Offset Vector Dimensions: 1 by 90
 0.00054359   −2.63705     6.29743     24.0083    −0.691296   −0.662844 1.17801e+13  −0.0467497   −0.940394 1.53269e−05
   −0.286624   −0.219566      31.0208    −0.482996   −0.928594 9.90511e+12   −0.293949     −1.2065 1.56513e−05    −0.34421
   −0.186094      31.0305    −0.479196   −0.934573 9.92854e+12   −0.292703     −1.22004  1.5736e−05   −0.331072   −0.199421
      31.0431    −0.478048   −0.936341 9.88561e+12   −0.288938     −1.21683 1.60963e−05   −0.302808   −0.231789      31.0776
    −0.481237   −0.935591 9.9424e+12   −0.286381     −1.21859 1.58991e−05   −0.286129   −0.254877      31.0303    −0.48204
```

−0.932435 9.83179e+12 −0.292364 −1.21741 1.58548e−05 −0.280131 −0.241095 31.0449 −0.479703 −0.932668
9.93471e+12 −0.289403 −1.21405 1.63669e−05 −0.232444 −0.347459 23.977 −0.661172 −0.771309 9.74863e+12
−0.211929 −1.21972 1.83216e−05 −0.209075 −0.514383 22.562 −0.581289 −0.685192 9.50765e+12 −0.364518
−1.06211 1.4744e−05 −0.0986884 −0.273749 7.71534 0.404481 −0.64956 9.93909e+12 0.1387 −1.28045

120

121 ==========

122

123 ----------

124 Burst: 1

125 Fingerprints: 0.000484142, −2.6124, 6.14313, 23.8671, −0.688413, −0.754609, 1.12116e+13, 0.0285509, −1.26072, 1.44675e−05, −0.302506, −0.564842, 30.6739, −0.499393, −0.933092, 1.0682e+13, 0.183254, −0.253016, 1.65275e−05, −0.0912049, −0.400581, 30.1432, −0.487574, −0.950747, 9.46865e+12, −0.212311, −1.41905, 1.1274e−05, −0.759928, 0.324143, 30.4293, −0.48934, −0.96954, 8.71915e+12, −0.294737, −1.57909, 1.48742e−05, −0.169879, −0.907481, 30.1696, −0.494958, −0.964221, 8.80993e+12, −0.246201, −1.62185, 1.50447e−05, −0.181404, −0.869718, 30.6034, −0.468557, −0.992598, 9.91971e+12, −0.536651, −0.706624, 1.42401e−05, −0.502983, −0.262833, 30.081, −0.495264, −0.940768, 1.06809e+13, 0.271238, 0.164766, 1.35402e−05, −0.209981, −0.404162, 23.6465, −0.653124, −0.801539, 9.10998e+12, −0.173066, −1.52532, 1.6674e−05, −0.100058, −0.892026, 21.9966, −0.608192, −0.6692, 8.41629e+12, −0.34357, −1.43081, 1.26325e−05, 0.10747, −0.390506, 7.15869, 0.209104, −0.935953, 9.57973e+12, 0.00453088, −1.49315

126 DNA Results: 2.21695, 1.8652, 6.1014, 2.58573, 1.38208, 1.57145, 2.21141, 3.24969, 1.75002, 1.19355

127 ----------

128

129 ----------

130 Burst: 2

131 Fingerprints: 0.000547583, −2.52409, 5.56325, 24.4746, −0.680105, −0.775479, 1.19888e+13, 0.19656, −0.803937, 1.46222e−05, −0.288606, −0.866538, 30.4022, −0.48049, −0.95131, 8.72298e+12, −0.297941, −1.55877, 1.51409e−05, −0.204184, −0.379061, 30.4292, −0.462755, −0.977408, 9.23294e+12, −0.240453, −1.62684, 1.32202e−05, −0.0847037, −0.391554, 30.3984, −0.475175, −0.97645, 9.91199e+12, −0.521736, −0.749453, 1.58215e−05, −0.535532, −0.700479, 30.2888, −0.475259, −0.966004, 1.05999e+13, 0.238615, −0.00744286, 1.5033e−05, −0.0767738, −0.521628, 30.4633, −0.481944, −0.951706, 9.01269e+12, −0.255107, −1.46575, 1.30094e−05, −0.0498481, −0.817803, 30.5269, −0.464966, −0.954613, 8.77376e+12, −0.321888, −1.54646, 1.62344e−05, −0.139222, −0.816018, 23.4088, −0.652444, −0.811476, 8.85937e+12, −0.147261, −1.62803, 1.5216e−05, −0.208534, −0.495012, 21.8262, −0.564223, −0.700463, 9.97947e+12, −0.851366, 0.619849, 1.35183e−05, 0.396515, −0.502405, 7.0404, 0.197694, −0.984181, 9.40135e+12, −0.0638478, −1.67356

132 DNA Results: 2.08888, 1.68626, 6.11482, 2.54044, 1.17361, 1.38759, 2.40474, 3.38157, 1.63051, 0.836388

133 ----------

134 ...

135 ...

136 ...

137 ...

138 ----------

139 Burst: 1906

140 Fingerprints: 0.000462542, −2.6257, 6.3197, 24.1031, −0.602659, −0.874896, 1.01729e+13, 0.0660602, −1.25633, 1.30733e−05, −0.590974, 0.0325582, 30.684, −0.442804, −1.02646, 1.03071e+13, 0.297578, 0.119069, 1.33052e−05, −0.249575, 0.355452, 30.9752, −0.411574, −1.06948, 9.37987e+12, −0.202414, −1.53203, 1.39997e−05, −0.544521, 0.492708, 31.0575, −0.421406, −1.02555, 8.82965e+12, −0.29291, −1.64249, 1.4321e−05, −0.0658905, −0.489685, 31.0135, −0.436565, −1.03532, 9.03493e+12, −0.252445, −1.72479, 1.52498e−05, −0.626062, 0.00840969, 30.9541, −0.43263, −1.04646, 9.73887e+12, −0.486588, −0.896012, 1.07034e−05, −0.635349, 0.137133, 30.662, −0.447852, −1.01515, 1.06774e+13, 0.236712, −0.0599057, 1.80834e−05, −0.568642, −0.0407675, 23.887, −0.584813, −0.907803, 9.16933e+12, −0.125612, −1.67471, 1.66455e−05, −0.325289, −0.110003, 22.8192, −0.572374, −0.719272, 9.36533e+12, −0.375178, −1.45231, 1.62984e−05, −0.206892, −0.742023, 8.07163, 0.647993, −0.544134, 8.99095e+12, 0.129211, −1.73623

141 DNA Results: 2.08485, 1.76511, 6.14833, 2.52914, 1.26536, 1.36921, 2.20284, 3.24735, 1.5724, 1.0177

142 ----------

143

144 ----------

145 Burst: 1907

```
Fingerprints: 0.00058104, -2.51017, 5.37284, 24.6607, -0.64132, -0.844598, 1.14472e+13, -0.0216109, -1.32158, 1.0891e-05,
    -0.00529928, -0.56346, 30.943, -0.457444, -0.976167, 1.0606e+13, 0.123451, -0.569941, 1.21239e-05, -0.398005, 0.898912,
    30.6674, -0.455931, -0.972589, 9.29122e+12, -0.283727, -1.76513, 1.1473e-05, -0.370064, -0.524713, 30.3333, -0.462905,
    -0.987202, 8.58564e+12, -0.283802, -1.78161, 1.30263e-05, 0.0928206, -0.146007, 30.649, -0.466955, -0.983474, 9.19419e+12,
     -0.254549, -1.7973, 1.1591e-05, -0.204375, -0.241568, 30.6361, -0.441498, -1.01157, 1.04161e+13, -0.562115, -0.6741,
    1.39238e-05, 0.24214, -0.21074, 30.7725, -0.459178, -0.998894, 1.04556e+13, 0.138324, -0.600393, 1.16295e-05, 0.0705197,
    -0.705736, 23.6096, -0.639583, -0.813336, 9.06226e+12, -0.14256, -1.8012, 1.65229e-05, 0.064139, -0.692495, 22.143,
    -0.58209, -0.674799, 8.29928e+12, -0.295043, -1.75859, 1.48085e-05, -0.124188, -0.0900506, 6.1492, 0.545806, -0.355956,
    9.12795e+12, 0.121215, -1.87803
DNA Results: 2.07239, 1.70087, 6.09538, 2.48023, 1.24685, 1.45615, 2.29295, 3.28073, 1.5466, 0.799719
--------------------------------------------------------------------------------
```

Appendix D. Source Code

The air monitor's Python code was not included because it can easily be reproduced using *gnuradio-companion*. The *packet_sink* and *Dna_detector_ccf* blocks source code were created using *gr_modtool*. Some pure virtual public functions were added to the header files to give the user access to the private implementation files as setters and getters. The SWIG generated Python functions will have access to the virtual public functions. The *packet_sink* and *Dna_detector_ccf* XML block files were modified a to provide the users the ability to save and load files with a GUI instead of just a name; a drop down menu was added for the debug option; and several "On"/"Off" and "Yes"/"No" drop downs for the options for the blocks.

The classes listed below were broken down to make them a little more readable. Even though everything compiled without any flags or errors, there were runtime issues with the SWIG generated *packet_sink* Python code because the DNA buffer class, base packet class, IEEE 802.15.4 packet class, file read implementation class, file store base class, and file store implementation classes were not being detected. Due to time constraints and my inexperience with SWIG, the class definitions were inserted into the packet_sink_impl.h header file while the source code was inserted into packet_sink_impl.cc to make everything work as intended.

D.1 Packet Sink Block Source Code

D.1.1 Packet Sink C++ Code.

```
1  /*************************************************************************************************************************
       ***
2  *preamble_sink.cc class
3  *************************************************************************************************************************
       **/
4  /* -*- c++ -*- */
5  /*
6   * Copyright 2018 gr-ieee802_15_4 author.
7   *
```

```
 8   * This is free software; you can redistribute it and/or modify
 9   * it under the terms of the GNU General Public License as published by
10   * the Free Software Foundation; either version 3, or (at your option)
11   * any later version.
12   *
13   * This software is distributed in the hope that it will be useful,
14   * but WITHOUT ANY WARRANTY; without even the implied warranty of
15   * MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the
16   * GNU General Public License for more details.
17   *
18   * You should have received a copy of the GNU General Public License
19   * along with this software; see the file COPYING.  If not, write to
20   * the Free Software Foundation, Inc., 51 Franklin Street,
21   * Boston, MA 02110-1301, USA.
22   */
23
24  #ifndef INCLUDED_IEEE802_15_4_PREAMBLE_SINK_H
25  #define INCLUDED_IEEE802_15_4_PREAMBLE_SINK_H
26
27  #include <ieee802_15_4/api.h>
28  #include <gnuradio/block.h>
29
30  namespace gr {
31    namespace ieee802_15_4 {
32      /*!
33       * SAVE enable/disable saving file statistics
34       * or everything else.
35       */
36      enum SAVE{
37        NO = 0,
38        YES = 1
39      };
40
41      /*!
42       * CRC will be used to determine if either crc verified data will be output
43       * or everything else.
44       */
45      enum CRC{
46        ALL_DATA = 0,
47        CRC_ONLY = 1
48      };
49
50      /*!
51       * DebugType will be used to determine the level of debugging outputs that will be enabled/disabled
52       */
53      enum DebugType{
54        ALL_OFF = 0,
55        CHIP_ON = 1,
56        PACKET_ON = 2,
57        USRP_ON = 4,
58        CHIP_PACKET_ON = 3,
59        CHIP_USRP_ON = 5,
60        PACKET_USRP_ON = 6,
61        ALL_ON = 7
```

```
62      };
63
64      /*!
65      *  Class: preamble_sink
66      *  Author: Schmid, Thomas; Bloessl, Bastian; Cruz, Frankie
67      *  Description: the class is directly derived from Bastian Bloessl's
68      *                    packet_sink class from his IEEE802.15.4  It is the same
69      *               code with a few minor modifications that allow the RX
70      *               802.15.4 preamble to be sent once it has been detected
71      *  Generated: Thurs Nov 8 15:30:18 2018
72      *  Modified: Sat Feb 2 08:00:23 2018
73      *  Build Version: 1.16
74      *  Changes: -Fixed short byte statistic
75      *           -Cleaned code up a bit
76      *           -Fixed Buffer placement...
77      */
78      class IEEE802_15_4_API preamble_sink : virtual public gr::block
79      {
80        public:
81          typedef boost::shared_ptr<preamble_sink> sptr;
82
83          /*!
84          * Make preambe_sink
85          *
86          * param samp_rate is the sample rate of the system
87          * param buffer_size is an array length consisting of previous bursts
88          * param threshold is the error threshold of the detected chips
89          * param debug is the debug output message setting
90          * param crc is the crc verified vs non-verified acceptance setting
91          * param burst_trigger will set the starting threshold of detection for normalized preamble
92          * param save wi enable/disable a file save of the packets
93          * param save_file is the loction of where the file will be saved
94          */
95          static sptr make(float samp_rate, unsigned int threshold, unsigned int buffer_size,
96                           float burst_trigger, DebugType debug, CRC crc,
97                           SAVE save_stats_switch, std::string save_stats_file);
98
99          virtual void set_threshold(const unsigned int &threshold) = 0;
100         virtual void set_samp_rate(const float &samp_rate) = 0;
101         virtual void set_buffer_size(const unsigned int &buffer_size) = 0;
102         virtual void set_burst_trigger(const float &burst_trigger) = 0;
103         virtual void set_debug(const DebugType &debug) = 0;
104         virtual void set_crc(const CRC &crc) = 0;
105         virtual void set_save_stats_switch(const SAVE &save_stats_switch) = 0;
106         virtual void set_save_stats_file(const std::string &save_stats_file) = 0;
107
108         virtual unsigned int get_threshold() const = 0;
109         virtual float get_samp_rate() const = 0;
110         virtual unsigned int get_buffer_size() const = 0;
111         virtual float get_burst_trigger() const = 0;
112         virtual DebugType get_debug() const = 0;
113         virtual SAVE get_save_stats_switch() const = 0;
114         virtual std::string get_save_stats_file() const = 0;
115     };
```

```
116
117     } // namespace ieee802_15_4
118   } // namespace gr
119   #endif /* INCLUDED_IEEE802_15_4_PREAMBLE_SINK_H */
120
121   /*************************************************************************************************************************
          ***
122    *preamble_sink_impl.h implementation class definitions
123   *************************************************************************************************************************
          **/
124   /* -*- c++ -*- */
125   /*
126    * Copyright 2018 gr-ieee802_15_4 author.
127    *
128    * This is free software; you can redistribute it and/or modify
129    * it under the terms of the GNU General Public License as published by
130    * the Free Software Foundation; either version 3, or (at your option)
131    * any later version.
132    *
133    * This software is distributed in the hope that it will be useful,
134    * but WITHOUT ANY WARRANTY; without even the implied warranty of
135    * MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the
136    * GNU General Public License for more details.
137    *
138    * You should have received a copy of the GNU General Public License
139    * along with this software; see the file COPYING.  If not, write to
140    * the Free Software Foundation, Inc., 51 Franklin Street,
141    * Boston, MA 02110-1301, USA.
142    */
143
144   #ifndef INCLUDED_IEEE802_15_4_PREAMBLE_SINK_IMPL_H
145   #define INCLUDED_IEEE802_15_4_PREAMBLE_SINK_IMPL_H
146
147   #include <ieee802_15_4/preamble_sink.h>
148   #include <cstdio>
149   #include <errno.h>
150   #include <sys/types.h>
151   #include <sys/stat.h>
152   #include <fcntl.h>
153   #include <stdexcept>
154   #include <cstring>
155   #include <gnuradio/blocks/count_bits.h>
156   #include <iostream>
157   #include <tuple>
158   #include <cmath>
159   #include <sstream>
160   #include <iostream>
161   #include <boost/thread.hpp>
162   #include <boost/thread/mutex.hpp>
163   #include <typeinfo>
164   #include <iomanip>
165   #include <ctime>
166
167   // win32 (mingw/msvc) specific
```

```
168 #ifdef HAVE_IO_H
169 #include <io.h>
170 #endif
171 #ifdef O_BINARY
172 #define OUR_O_BINARY O_BINARY
173 #else
174 #define OUR_O_BINARY 0
175 #endif
176
177 // should be handled via configure
178 #ifdef O_LARGEFILE
179 #define OUR_O_LARGEFILE O_LARGEFILE
180 #else
181 #define OUR_O_LARGEFILE 0
182 #endif
183
184 namespace gr {
185   namespace ieee802_15_4 {
186  /*!
187     * Class: preamble_sink_impl
188     * Author: Schmid, Thomas;Bloessl, Bastian; Cruz, Frankie
189     * Description: the class is the implementation file of
190     *              preamble_sink.h.  See preamble_sink.h
191     *              for more information about this class
192     * Generated: Thurs Nov 8 15:30:18 2018 Wed Nov 28 10:30:11 2018
193     * Modified: Dec 01 13:30:01 2018
194     * Build Version: 1.6
195     * Changes: See preamble_sink.h
196     */
197
198     // this is the mapping between chips and symbols if we do
199     // a fm demodulation of the O-QPSK signal. Note that this
200     // is different than the O-QPSK chip sequence from the
201     // 802.15.4 standard since there there is a translation
202     // happening.
203     // See "CMOS RFIC Architectures for IEEE 802.15.4 Networks",
204     // John Notor, Anthony Caviglia, Gary Levy, for more details.
205     static const unsigned int CHIP_MAPPING[] = {
206                         1618456172,
207                         1309113062,
208                         1826650030,
209                         1724778362,
210                         778887287,
211                         2061946375,
212                         2007919840,
213                         125494990,
214                         529027475,
215                         838370585,
216                         320833617,
217                         422705285,
218                         1368596360,
219                         85537272,
220                         139563807,
221                         2021988657};
```

```
222
223
224     static const int MAX_PKT_LEN     = 128 -  1; // remove header and CRC
225     static const int MAX_LQI_SAMPLES = 8; // Number of chip correlation samples to take
226
227     class preamble_sink_impl : public preamble_sink
228     {
229       private:
230         enum {STATE_SYNC_SEARCH, STATE_HAVE_SYNC, STATE_HAVE_HEADER} d_state;
231
232         unsigned int       d_sync_vector;           // 802.15.4 standard is 4x 0 bytes and 1x0xA7
233         unsigned int       d_threshold = 10;        // how many bits may be wrong in sync vector
234
235         unsigned int       d_shift_reg;             // used to look for sync_vector
236         int                d_preamble_cnt;          // count on where we are in preamble
237         int                d_chip_cnt;              // counts the chips collected
238
239         unsigned int       d_header;                // header bits
240         int                d_headerbitlen_cnt;      // how many so far
241
242         unsigned char      d_packet[MAX_PKT_LEN];   // assembled payload
243         unsigned char      d_packet_byte;           // byte being assembled
244         int                d_packet_byte_index;     // which bit of d_packet_byte we're working on
245         int                d_packetlen;             // length of packet
246         int                d_packetlen_cnt;         // how many so far
247         int                d_payload_cnt;           // how many bytes in payload
248
249         unsigned int       d_lqi;                   // Link Quality Information
250         unsigned int       d_lqi_sample_count;
251
252         float d_burst_trigger = 0.3f;               // default preamble burst trigger
253         float d_samp_rate = 4e6f;                   // block system's sample rate
254         int d_chip_debug = 0;                       // very verbose output for almost each sample
255         int d_pack_debug = 0;                       // less verbose output for higher level debugging
256         int d_usrp_debug = 0;                       // USRP verbose output for debugging
257         int d_crc_set = 0;                          // CRC data input setting
258         int d_save_switch_set = 0;                  // Save switch input setting
259         int d_crc_good_payload = 0;                 // good data packet counter
260         int d_crc_bad_payload = 0;                  // bad data packet counter
261         int d_short_payload = 0;                    // short payload counter
262         int d_recent_packet_length = 0;             // sanity check for packet length
263         int d_removed_preambles = 0;                // detected preambles that were too short to process
264         int d_sent_preambles = 0;                   // detected preambles that were sent for RFDNA processing
265         bool d_preamble_processed = false;          // Activates preamble processing
266         unsigned int d_buffer_size;                      // previous storage buffer length
267         bool d_prev_buffer_activated = false;
268
269         DebugType d_debug = ALL_OFF;                // Default debug state
270         CRC d_crc = ALL_DATA;                       //All on by default
271         ieee802_15_4_packet d_phy_802_15_4;         // ieee802.15.4 packet with size info
272
273         SAVE d_save_stats_switch = NO;           // off by default
274         std::string d_save_stats_file;              // file location where to save stats
275         std::stringstream d_msg_stream;             // handles string messages
```

```
276         std::shared_ptr<file_store_impl> d_stats_writer; // for statistics output file
277
278         // FIX ME
279         char buf[256]; // PDDU Packet Buffer
280         dna_buffer d_prev_usrp_collect_buffer;          // previous run usrp buffered data
281         dna_buffer d_current_preamble_buffer;           // current run's detected buffer data for crc processing
282         dna_buffer d_crc_preamble_buffer;               // crc evaluated buffered data
283
284         // enter_search, enter_have_sync,
285         // and enter_have_header are state
286         // functions used to set the private
287         // varriables based on if the RX
288         // signal is searching, found, and
289         // parsed ieee 802.15.4 packets
290         void enter_search();
291         void enter_have_sync();
292         void enter_have_header(const int &payload_len);
293
294       public:
295         preamble_sink_impl(float samp_rate, unsigned int threshold, unsigned int buffer,
296                            float burst_trigger, DebugType debug, CRC crc,
297                            SAVE save_stats_switch, std::string save_stats_file);
298         ~preamble_sink_impl();
299
300         // Where all the action really happens
301         void forecast (int noutput_items, gr_vector_int &ninput_items_required);
302
303         int general_work(int noutput_items,
304             gr_vector_int &ninput_items,
305             gr_vector_const_void_star &input_items,
306             gr_vector_void_star &output_items);
307
308         // decode_chips takes in the value of the RX
309         // chips as an integer and performs a XOR comparison
310         // between the CHIP_MAPPING vector to return a 1-symbol
311         // via a byte equivalent to 1 of the 16 mapped constellation
312         // values.
313         unsigned char decode_chips(const unsigned int &chips);
314
315         // slice will be used to determine if an input bit is
316         // 1 or 0 for the shift register
317         int slice(const float &x);
318
319         // setter & getter for error threshold
320         void set_threshold(const unsigned int &threshold);
321         unsigned int get_threshold() const;
322
323         // getters and setters to get/set sample rate
324         void set_samp_rate(const float &samp_rate);
325         float get_samp_rate() const;
326
327         // getters and setters for buffer size
328         void set_buffer_size(const unsigned int &buffer);
329         unsigned int get_buffer_size() const;
```

```
330
331         //getters and setters for burst trigger
332         void set_burst_trigger(const float &burst_trigger);
333         float get_burst_trigger() const;
334
335         // getters and setters to get/set debug settings
336         void set_debug(const DebugType &debug);
337         DebugType get_debug() const;
338
339         // getters and setters to get/set crc
340         // verified packets only or everything
341         void set_crc(const CRC &crc);
342         CRC get_crc() const;
343
344         // getters and setters for stat_file functions
345         void set_save_stats_switch(const SAVE &save_stats_switch);
346         void set_save_stats_file(const std::string &save_stats_file);
347         SAVE get_save_stats_switch() const;
348         std::string get_save_stats_file() const;
349
350         // function used in mac.cc from gr-ieee805-15-4
351         // to verify data validity of raw data
352         uint16_t crc16(const char *buf, const int &len);
353
354         // shortcut to clear stringstream
355         void clear_stream();
356
357         // generic print print function that for vector
358         // inputs
359         void vector_print(const std::string &label, const std::vector<int> &input);
360
361         // returns a trigger-set/sample adjusted preamble from the passed in buffer
362         std::tuple<dna_buffer, bool> normalize_preamble(const dna_buffer &buffer,
363                                                         const int &max_return_size,
364                                                         const float &burst_trigger);
365
366         // NOTE: Didn't finish, but will if I have time...
367         // Filter_burst is going to filter the absolute magnitude of the burst with an n-taps.
368         // The magnitude pulse scaled and normalized to 1 and the index point where the filtered
369         // burst exceeds the user-given threshold
370         std::tuple<dna_buffer, int> filter_burst(const dna_buffer &buffer, const int &filter_taps);
371     };
372
373   } // namespace ieee802_15_4
374 } // namespace gr
375 #endif /* INCLUDED_IEEE802_15_4_PREAMBLE_SINK_IMPL_H */
376
377 /*************************************************************************************************************************
       ***
378  *preamble_sink_impl.cc Source Code
379 *************************************************************************************************************************
       **/
380 #include <gnuradio/io_signature.h>
381 #include "preamble_sink_impl.h"
```

```
382 //#include <gnuradio/block.h>
383
384 namespace gr {
385   namespace ieee802_15_4 {
386     /*************************************
387     * preamble_sink source code section
388     *************************************/
389     preamble_sink::sptr
390     preamble_sink::make(float samp_rate, unsigned int threshold, unsigned int buffer_size,
391                         float burst_trigger,DebugType debug, CRC crc,
392                         SAVE save_stats_switch, std::string save_stats_file)
393     {
394       return gnuradio::get_initial_sptr
395         (new preamble_sink_impl(samp_rate, threshold, buffer_size,
396                                 burst_trigger, debug, crc,
397                                 save_stats_switch, save_stats_file));
398     }
399
400     /*************************************
401     * preamble_sink_impl source code section
402     *************************************/
403     /*
404      * The private constructor
405      */
406     preamble_sink_impl::preamble_sink_impl(float samp_rate, unsigned int threshold, unsigned int buffer_size,
407                                            float burst_trigger, DebugType debug, CRC crc,
408                                            SAVE save_stats_switch, std::string save_stats_file)
409       : gr::block("preamble_sink",
410               gr::io_signature::make2(2,2, sizeof(float), sizeof(gr_complex)),
411               gr::io_signature::make2(2, 2, sizeof(gr_complex), sizeof(gr_complex)))
412     {
413       d_sync_vector = 0xA7;
414       d_samp_rate = samp_rate;
415       d_threshold = threshold;
416       d_save_stats_file = save_stats_file;
417       d_burst_trigger = burst_trigger;
418       set_debug(debug);
419       set_crc(crc);
420       set_save_stats_switch(save_stats_switch);
421       set_buffer_size(buffer_size);
422
423       //Set sample rate for our packet size calculations
424       d_phy_802_15_4.set_sample_rate(d_samp_rate);
425
426       std::cout << "\nPreamble_sink sample rate set to " << samp_rate << std::endl;
427
428       // file name and save settings set here
429       if(d_save_stats_switch == SAVE::YES)
430       {
431         // from stackoverflow.com, just a quick way to append time/date to a filename
432         auto t = std::time(nullptr);
433         auto tm = *std::localtime(&t);
434         d_msg_stream << "_" << std::put_time(&tm, "%d%b%y_%R") << ".txt";
435         d_save_stats_file.append(d_msg_stream.str());
```

```
436             clear_stream();
437
438             std::cout << "\nFile stats set to save at " << d_save_stats_file << ".\n" << std::endl;
439             d_stats_writer = std::make_shared<file_store_impl>(sizeof(char), d_save_stats_file.c_str(),
440                                                               false, false);
441
442             d_msg_stream << "\n================================================================================" << "\n";
443             d_msg_stream <<  "Collection started on " << std::put_time(&tm, "%F_%T");
444             d_msg_stream <<  "\nBuffer size set to  " << d_buffer_size;
445             d_msg_stream <<  "\nSample Rate at " << samp_rate << " Samp/sec";
446             d_msg_stream <<  "\nPreamble sample length at " << samp_rate << " Samp/sec is " << d_phy_802_15_4.
                    get_preamble_len_samples();
447             d_msg_stream <<  "\nPacket sample length at " << samp_rate << " Samp/sec is " << d_phy_802_15_4.get_packet_len_samples()
                    ;
448             d_msg_stream << "\n================================================================================" << "\n";
449             d_stats_writer->store_data(d_msg_stream.str().size(), (void*)d_msg_stream.str().c_str());
450             clear_stream();
451           }
452
453           // Link Quality Information
454           d_lqi = 0;
455           d_lqi_sample_count = 0;
456
457           //need to convert to a int for this to work
458           set_output_multiple((int)round(d_phy_802_15_4.get_sym_to_chip_mult()));
459           set_min_output_buffer(1,4088l); //hard coded for now to ensure a proper output for passthrough usrp data...need to fix
                  later
460
461           if(d_chip_debug)
462           {
463             fprintf(stderr, "syncvec: %x, threshold: %d\n", d_sync_vector, d_threshold),fflush(stderr);
464           }
465           enter_search();
466
467           message_port_register_out(pmt::mp("out"));
468         }
469
470         /*
471          * Our virtual destructor.
472          */
473         preamble_sink_impl::~preamble_sink_impl()
474         {
475         }
476
477         void
478         preamble_sink_impl::forecast (int noutput_items, gr_vector_int &ninput_items_required)
479         {
480           /************************Special Note*************************************************
481           ***Need to see if this is adjustable before and after compilation for different Samp Rates*****
482           ****************************************************************************************/
483
484           // need to fix ieee802_15_4_packet class to better handle inputs
485           // original implementation was blowing up block
486           // now this needs to be hard coded for the moment
```

```
487       ninput_items_required[0] = 1022;
488       ninput_items_required[1] = 2044;
489     }
490
491     int
492     preamble_sink_impl::general_work (int noutput_items,
493                       gr_vector_int &ninput_items,
494                       gr_vector_const_void_star &input_items,
495                       gr_vector_void_star &output_items)
496     {
497       const float *inbuf = (const float *) input_items[0]; // input stream M&M stream of floats for detection
498       const gr_complex *in_rx = (const gr_complex *) input_items[1]; // input stream of RX data
499
500       int ninput = ninput_items[0]; // input number of detected float data
501       int ninput_rx = ninput_items[1]; // input number of RX data
502
503       gr_complex *out_rx = (gr_complex *) output_items[0]; // output RX stream for detected preambles
504       gr_complex *out_usrp = (gr_complex *) output_items[1]; //input to output raw stream
505
506       int count = 0;
507       static std::vector<int> preamble_marker; // used to store preamble markers per each general_work itteration
508       static std::vector<int> sync_marker; // used to store the sync markers per general_work itteration
509       static std::vector<int> header_marker; // used to store the header markers per general_work itteration
510
511       int i = 0;
512
513       if (d_chip_debug)
514         fprintf(stderr,">>> Entering state machine\n"),fflush(stderr);
515
516       // The burst buffer is going to determine how many previous bursts will be "searched"
517       // through once a proper packet has been detected.  If the buffer is bigger than the
518       // user set limit, the FIFO structure will pop off the front burst samples
519       if(d_prev_usrp_collect_buffer.get_burst_length() > d_buffer_size)
520       {
521         d_prev_usrp_collect_buffer.pop_front_burst_samples();
522        }
523       while(count < ninput) {
524         switch(d_state) {
525
526         case STATE_SYNC_SEARCH:    // Look for sync vector
527           if (d_chip_debug)
528             fprintf(stderr,"SYNC Search, ninput=%d syncvec=%x\n", ninput, d_sync_vector),fflush(stderr);
529
530           while (count < ninput) {
531
532             if(slice(inbuf[count++]))
533               d_shift_reg = (d_shift_reg << 1) | 1;
534             else
535               d_shift_reg = d_shift_reg << 1;
536
537             if(d_preamble_cnt > 0){
538               d_chip_cnt = d_chip_cnt+1;
539             }
540
```

```
541             // The first if block syncronizes to chip sequences.
542             if(d_preamble_cnt == 0){
543               unsigned int threshold;
544               threshold = gr::blocks::count_bits32((d_shift_reg & 0x7FFFFFFE) ^ (CHIP_MAPPING[0] & 0x7FFFFFFE));
545               if(threshold < d_threshold) {
546                 //  fprintf(stderr, "Threshold %d d_preamble_cnt: %d\n", threshold, d_preamble_cnt);
547                 //if ((d_shift_reg&0xFFFFFE) == (CHIP_MAPPING[0]&0xFFFFFE)) {
548                 if (d_pack_debug)
549                   fprintf(stderr,"Found 0 in chip sequence\n"),fflush(stderr);
550                 // we found a 0 in the chip sequence
551                 d_preamble_cnt+=1;
552                 //fprintf(stderr, "Threshold %d d_preamble_cnt: %d\n", threshold, d_preamble_cnt);
553               }
554             } else {
555               // we found the first 0, thus we only have to do the calculation every 32 chips
556               if(d_chip_cnt == 32){
557                 d_chip_cnt = 0;
558
559                 if(d_packet_byte == 0) {
560                   if (gr::blocks::count_bits32((d_shift_reg & 0x7FFFFFFE) ^ (CHIP_MAPPING[0] & 0xFFFFFFFE)) <= d_threshold) {
561                     if (d_pack_debug)
562                       fprintf(stderr,"Found %d 0 in chip sequence\n", d_preamble_cnt),fflush(stderr);
563                     // we found an other 0 in the chip sequence
564                     d_packet_byte = 0;
565                     d_preamble_cnt ++;
566                   } else if (gr::blocks::count_bits32((d_shift_reg & 0x7FFFFFFE) ^ (CHIP_MAPPING[7] & 0xFFFFFFFE)) <=
                          d_threshold) {
567                     if (d_pack_debug)
568                       fprintf(stderr,"Found first SFD\n"),fflush(stderr);
569                     d_packet_byte = 7 << 4;
570
571                   } else {
572                     // we are not in the synchronization header
573                     if (d_pack_debug)
574                       fprintf(stderr, "Wrong first byte of SFD. %u\n", d_shift_reg), fflush(stderr);
575                     enter_search();
576                     break;
577                   }
578
579                 } else {
580                   if (gr::blocks::count_bits32((d_shift_reg & 0x7FFFFFFE) ^ (CHIP_MAPPING[10] & 0xFFFFFFFE)) <= d_threshold) {
581                     d_packet_byte |= 0xA;
582                     if (d_pack_debug)
583                       fprintf(stderr,"Found sync, 0x%x\n", d_packet_byte),fflush(stderr);
584                     // found SFD
585                     // setup for header decode
586
587                     // each count number will be used to find
588                     // a relation between the usrp preambles
589                     if(d_debug)
590                     {
591                       preamble_marker.push_back(count);
592                     }
593
```

```
594                     // if there's any data in from the previous run it will be appended as
595                     // chances are that it will contain the preamble with the current data,
596                     // only the previous input will be passed through as a safety precaution
597                     // if the previously collected buffer doesn't exist then only the current
598                     // data will be passed with the possibility of not receiving the preamble
599                     if(d_prev_usrp_collect_buffer.is_activated()){
600                       d_prev_buffer_activated = true;
601                       d_current_preamble_buffer.append_buffer_data(d_prev_usrp_collect_buffer);
602                       for(int c = 0; c < ninput_rx; c++)
603                       {
604                         d_current_preamble_buffer.append_buffer_data(in_rx[c]);
605                       }
606
607                     }else{
608                       d_prev_buffer_activated = false;
609                       d_current_preamble_buffer.store_preamble_data(ninput_rx, in_rx);
610                     }
611
612                     enter_have_sync();
613                     break;
614                   } else {
615                     if (d_chip_debug)
616                       fprintf(stderr, "Wrong second byte of SFD. %u\n", d_shift_reg), fflush(stderr);
617                     enter_search();
618                     break;
619                   }
620                 }
621               }
622             }
623           }
624           break;
625
626         case STATE_HAVE_SYNC:
627           if (d_pack_debug)
628             fprintf(stderr,"Header Search bitcnt=%d, header=0x%08x\n", d_headerbitlen_cnt, d_header),
629             fflush(stderr);
630
631           while (count < ninput) {       // Decode the bytes one after another.
632             if(slice(inbuf[count++]))
633               d_shift_reg = (d_shift_reg << 1) | 1;
634             else
635               d_shift_reg = d_shift_reg << 1;
636
637             d_chip_cnt = d_chip_cnt+1;
638
639             if(d_chip_cnt == 32){
640               d_chip_cnt = 0;
641               unsigned char c = decode_chips(d_shift_reg);
642               if(c == 0xFF){
643                 // something is wrong. restart the search for a sync
644                 if(d_pack_debug)
645                   fprintf(stderr, "Found a not valid chip sequence! %u\n", d_shift_reg), fflush(stderr);
646
647                 enter_search();
```

```
648                 break;
649               }
650
651               if(d_packet_byte_index == 0){
652                 d_packet_byte = c;
653               } else {
654                 // c is always < 15
655                 d_packet_byte |= c << 4;
656               }
657               d_packet_byte_index = d_packet_byte_index + 1;
658               if(d_packet_byte_index%2 == 0){
659                 // we have a complete byte which represents the frame length.
660                 int frame_len = d_packet_byte;
661                 if(frame_len <= MAX_PKT_LEN){
662
663                   // keep track of the found sync markers
664                   // to see correlate to good usrp markers
665                   if(d_debug)
666                   {
667                     sync_marker.push_back(count);
668                   }
669
670                   enter_have_header(frame_len);
671                 } else {
672                   enter_search();
673                 }
674                 break;
675               }
676             }
677           }
678           break;
679
680         case STATE_HAVE_HEADER:
681           if (d_pack_debug)
682             fprintf(stderr,"Packet Build count=%d, ninput=%d, packet_len=%d\n", count, ninput, d_packetlen),fflush(stderr);
683
684           while (count < ninput) {   // shift bits into bytes of packet one at a time
685             if(slice(inbuf[count++]))
686               d_shift_reg = (d_shift_reg << 1) | 1;
687             else
688               d_shift_reg = d_shift_reg << 1;
689
690             d_chip_cnt = (d_chip_cnt+1)%32;
691
692             if(d_chip_cnt == 0){
693               unsigned char c = decode_chips(d_shift_reg);
694               if(c == 0xff){
695                 // something is wrong. restart the search for a sync
696                 if(d_pack_debug)
697                   fprintf(stderr, "Found a not valid chip sequence! %u\n", d_shift_reg), fflush(stderr);
698
699                 enter_search();
700                 break;
701               }
```

```
702
703                 // the first symbol represents the first part of the byte.
704                 if(d_packet_byte_index == 0){
705                   d_packet_byte = c;
706                 } else {
707                   // c is always < 15
708                   d_packet_byte |= c << 4;
709                 }
710                 //fprintf(stderr, "%d: 0x%x\n", d_packet_byte_index, c);
711                 d_packet_byte_index = d_packet_byte_index + 1;
712                 if(d_packet_byte_index%2 == 0){
713                   // we have a complete byte
714                   if (d_pack_debug)
715                     fprintf(stderr, "packetcnt: %d, payloadcnt: %d, payload 0x%x, d_packet_byte_index: %d\n", d_packetlen_cnt,
                           d_payload_cnt, d_packet_byte, d_packet_byte_index), fflush(stderr);
716
717                   d_packet[d_packetlen_cnt++] = d_packet_byte;
718                   d_payload_cnt++;
719                   d_packet_byte_index = 0;
720
721                   if (d_payload_cnt >= d_packetlen){  // packet is filled, including CRC. might do check later in here
722                     unsigned int scaled_lqi = (d_lqi / MAX_LQI_SAMPLES) << 3;
723                     unsigned char lqi = (scaled_lqi >= 256? 255 : scaled_lqi);
724
725                     pmt::pmt_t meta = pmt::make_dict();
726                     meta = pmt::dict_add(meta, pmt::mp("lqi"), pmt::from_long(lqi));
727
728                     std::memcpy(buf, d_packet, d_packetlen_cnt);
729                     pmt::pmt_t payload = pmt::make_blob(buf, d_packetlen_cnt);
730
731
732                     //************* Pass and Analyze Preamble Data Here!!!!**********************
733                     // the header count will be used as a way to
734                     // correlate the header count with the USRP
735                     // data
736                     if(d_debug)
737                     {
738                       header_marker.push_back(count);
739                     }
740
741                      std::tuple<dna_buffer, bool> buffer_data;
742                      if(d_prev_buffer_activated)
743                      {
744                        buffer_data = std::move(normalize_preamble(d_current_preamble_buffer, ninput_rx, d_burst_trigger));
745                      }
746
747                     d_preamble_processed = std::get<1>(buffer_data);
748
749                     //based on the last run, it will determine if a
750                     //preamble met the criteria to be sent or not
751                     if(d_preamble_processed == true)
752                     {
753                       d_sent_preambles++;
754                     }else{
```

```
755                     d_removed_preambles++;
756                   }
757
758                   // raw data crc will be checked for validity and filtering
759                   // later on
760                   uint16_t crc_check = crc16(buf, d_packetlen_cnt);
761
762                   // if-else statements are a way to keep track of processing errors
763                   // of the general_work function based on mac_in
764                   // function from mac.cc from gr-ieee802.15.4
765                   d_recent_packet_length = d_packetlen;
766                   if(d_packetlen_cnt < 9)
767                   {
768                     d_short_payload++;
769                   }else if(crc_check)
770                   {
771                     d_crc_bad_payload++;
772                   }else
773                   {
774                     d_crc_good_payload++;
775                   }
776
777                   // the if/else conditions will check to see if the user will
778                   // accept only properly sized crc verified packet outputs or
779                   // any and everything that comes in packet-wise
780                   if(d_crc_set)
781                   {
782                     if(!crc_check && (d_packetlen_cnt < 9))
783                     {
784                       // might make a function later on to handle empty values
785                       // but a loop will suffice for now
786                       for(int c = 0; c < ninput_rx; c++)
787                       {
788                         d_crc_preamble_buffer[c] = gr_complex(0.0f, 0.0f);
789                       }
790
791                     }else
792                     {
793                       d_crc_preamble_buffer = d_prev_buffer_activated ? std::move(std::get<0>(buffer_data)) : std::move(
                              d_current_preamble_buffer);
794                     }
795                   }else
796                   {
797                       d_crc_preamble_buffer = d_prev_buffer_activated ? std::move(std::get<0>(buffer_data)) : std::move(
                              d_current_preamble_buffer);
798                   }
799
800                   //debug check copied directly from mac.cc
801                   //from gr-ieee802.15.4
802                   if(d_usrp_debug)
803                   {
804                     if(d_packetlen_cnt < 9)
805                     {
806                       fprintf(stderr, "\nDetected packet MAC frame too short"), fflush(stderr);
```

```
807                     }
808                     if(crc_check)
809                     {
810                       fprintf(stderr, "\nDetected packet MAC failed CRC check"), fflush(stderr);
811                     }else
812                     {
813                       fprintf(stderr, "\nDetected packet MAC passed CRC check\n"), fflush(stderr);
814                     }
815                   }
816
817                 if(d_save_stats_switch == SAVE::YES)
818                 {
819                   clear_stream();
820                   d_msg_stream << "\n================================================================================" <<
                           "\n";
821                   d_msg_stream << "Current Burst Sample Length: " << ninput_rx << "\n";
822                   if(d_prev_buffer_activated)
823                   {
824                     d_msg_stream << "Buffer + Detected Burst Sample length: ";
825                   }else
826                   {
827                     d_msg_stream << "Detected Burst Sample: ";
828                   }
829                   d_msg_stream << d_current_preamble_buffer.get_sample_length() << "\n";
830                   d_msg_stream << "Total Packets Detected: " << d_short_payload + d_crc_bad_payload + d_crc_good_payload << "\n
                           ";
831                   d_msg_stream << "Short Packets: " << d_short_payload << "\n";
832                   d_msg_stream << "Bad CRC Packets: " << d_crc_bad_payload << "\n";
833                   d_msg_stream << "Good CRC Packets: " << d_crc_good_payload << "\n";
834                   d_msg_stream << "Total Preambles Processed" << "\n";
835                   d_msg_stream << "of " << d_short_payload + d_crc_bad_payload + d_crc_good_payload << " Total Packets Detected:
                           ";
836                   d_msg_stream << d_removed_preambles + d_sent_preambles << "\n";
837                   d_msg_stream << "Preambles Accepted: " << d_sent_preambles << "\n";
838                   d_msg_stream << "Preambles Rejected: " << d_removed_preambles << "\n";
839                   d_msg_stream << "================================================================================" <<
                           "\n";
840                   d_stats_writer->store_data(d_msg_stream.str().size(), (void*)d_msg_stream.str().c_str());
841                 }
842
843                   message_port_pub(pmt::mp("out"), pmt::cons(meta, payload));
844
845                   if(d_pack_debug)
846                     fprintf(stderr, "Adding message of size %d to queue\n", d_packetlen_cnt);
847                   enter_search();
848                   break;
849                 }
850               }
851             }
852           }
853           break;
854
855         default:
856           assert(0);
```

```
857             break;
858
859           }
860         }
861
862
863         if(d_pack_debug)
864           fprintf(stderr, "Samples Processed: %d\n", ninput_items[0]), fflush(stderr);
865
866           consume(0, ninput_items[0]);
867
868         // Debug & Itteration Statistics for the blocks current run
869         if(d_usrp_debug && (d_crc_preamble_buffer.is_activated()))
870         {
871           fprintf(stderr,"++++++++++++++++++++++++++++++++++++++++++++++++++"), fflush(stderr);
872           fprintf(stderr, "\nM & M Timer Input Count: %d\tUSRP Input Count: %d",
873                   ninput, ninput_rx), fflush(stderr);
874           fprintf(stderr,"\nInheritted Output Item Count: %d", noutput_items), fflush(stderr);
875           fprintf(stderr,"\nPacket Length: %d", d_recent_packet_length), fflush(stderr);
876           fprintf(stderr, "\nTotal Processed Preambles: %d", (d_removed_preambles +
877                   d_sent_preambles)), fflush(stderr);
878           fprintf(stderr, "\nDropped Preambles: %d", d_removed_preambles), fflush(stderr);
879           fprintf(stderr, "\nSent Preambles: %d", d_sent_preambles), fflush(stderr);
880
881           vector_print("\nPreamble", preamble_marker);
882           vector_print("Sync", sync_marker);
883           vector_print("Header", header_marker);
884
885           fprintf(stderr, "\nTotal Run Numbers => Short Packets: %d\tBad CRC Packets: %d\tGood CRC Packets: %d\n",
886             d_short_payload, d_crc_bad_payload, d_crc_good_payload), fflush(stderr);
887
888           preamble_marker.clear();
889           sync_marker.clear();
890           header_marker.clear();
891           fprintf(stderr,"--------------------------------------------------"), fflush(stderr);
892         }
893
894         // The current input will be appended here to the FIFO buffer sturcture for the
895         // next itteration.
896         d_prev_usrp_collect_buffer.append_burst_sample_size(ninput_rx);
897
898         for(int c = 0; c < ninput_rx; c++ )
899         {
900           out_rx[c] = d_crc_preamble_buffer.is_activated() ? d_crc_preamble_buffer[c] : gr_complex(0.0F,0.0F);
901           d_prev_usrp_collect_buffer.append_buffer_data(in_rx[c]);
902           out_usrp[c] = in_rx[c];
903         }
904         d_crc_preamble_buffer.unset_buffer();
905
906         consume(0, 0);
907         consume(1, ninput_rx);
908
909         return ninput_rx;
910       }
```

```
911
912     void
913     preamble_sink_impl::enter_search()
914     {
915       if (d_chip_debug)
916       {
917         fprintf(stderr, "@ enter_search\n");
918       }
919
920       d_state = STATE_SYNC_SEARCH;
921       d_shift_reg = 0;
922       d_preamble_cnt = 0;
923       d_chip_cnt = 0;
924       d_packet_byte = 0;
925       d_current_preamble_buffer.unset_buffer();
926     }
927
928     void
929     preamble_sink_impl::enter_have_sync()
930     {
931       if (d_chip_debug)
932         {
933           fprintf(stderr, "@ enter_have_sync\n");
934         }
935
936       d_state = STATE_HAVE_SYNC;
937       d_packetlen_cnt = 0;
938       d_packet_byte = 0;
939       d_packet_byte_index = 0;
940
941       // Link Quality Information
942       d_lqi = 0;
943       d_lqi_sample_count = 0;
944     }
945
946     void
947     preamble_sink_impl::enter_have_header(const int &payload_len)
948     {
949       if (d_chip_debug)
950         fprintf(stderr, "@ enter_have_header (payload_len = %d)\n", payload_len);
951
952       d_state = STATE_HAVE_HEADER;
953       d_packetlen  = payload_len;
954       d_payload_cnt = 0;
955       d_packet_byte = 0;
956       d_packet_byte_index = 0;
957     }
958
959     unsigned char
960     preamble_sink_impl::decode_chips(const unsigned int &chips)
961     {
962       int i;
963       int best_match = 0xFF;
964       int min_threshold = 33; // Matching to 32 chips, could never have a error of 33 chips
```

```
965
966         for(i=0; i<16; i++)
967         {
968           // FIXME: we can store the last chip
969           // ignore the first and last chip since it depends on the last chip.
970           unsigned int threshold = gr::blocks::count_bits32((chips & 0x7FFFFFE) ^ (CHIP_MAPPING[i] & 0x7FFFFFE));
971
972           if (threshold < min_threshold)
973           {
974             best_match = i;
975             min_threshold = threshold;
976           }
977         }
978
979         if (min_threshold < d_threshold) {
980           if (d_chip_debug)
981           {
982             fprintf(stderr, "Found sequence with %d errors at 0x%x\n", min_threshold, (chips & 0x7FFFFFE) ^ (CHIP_MAPPING[
                    best_match] & 0x7FFFFFE)), fflush(stderr);
983           }
984
985           // LQI: Average number of chips correct * MAX_LQI_SAMPLES
986           //
987           if (d_lqi_sample_count < MAX_LQI_SAMPLES)
988           {
989             d_lqi += 32 - min_threshold;
990             d_lqi_sample_count++;
991           }
992
993           return std::move((char)best_match & 0xF);
994         }
995
996         return std::move(0xFF);
997       }
998
999       int
1000      preamble_sink_impl::slice(const float &x)
1001      {
1002        return std::move(x > 0 ? 1 : 0);
1003      }
1004
1005      void
1006      preamble_sink_impl::set_threshold(const unsigned int &threshold)
1007      {
1008        d_threshold = threshold;
1009      }
1010
1011      unsigned int
1012      preamble_sink_impl::get_threshold() const
1013      {
1014        return d_threshold;
1015      }
1016
1017      void
```

```
1018    preamble_sink_impl::set_samp_rate(const float &samp_rate)
1019    {
1020      d_samp_rate = samp_rate;
1021      d_phy_802_15_4.set_sample_rate(samp_rate);
1022    }
1023
1024    void
1025    preamble_sink_impl::set_buffer_size(const unsigned int &buffer_size)
1026    {
1027      if(buffer_size <=0)
1028      {
1029        std::cout << "\nBuffer size too small... It's now set to 1" << std::endl;
1030        d_buffer_size = 1;
1031      }else
1032      {
1033        d_buffer_size = buffer_size;
1034      }
1035    }
1036
1037    unsigned int
1038    preamble_sink_impl::get_buffer_size() const
1039    {
1040      return d_buffer_size;
1041    }
1042
1043    float
1044    preamble_sink_impl::get_samp_rate() const
1045    {
1046      return d_samp_rate;
1047    }
1048
1049    void
1050    preamble_sink_impl::set_burst_trigger(const float &burst_trigger)
1051    {
1052      d_burst_trigger = burst_trigger;
1053    }
1054
1055    float
1056    preamble_sink_impl::get_burst_trigger() const
1057    {
1058      return d_burst_trigger;
1059    }
1060
1061    void
1062    preamble_sink_impl::set_debug(const DebugType &debug)
1063    {
1064      d_debug = debug;
1065
1066      // quick bitwise comparison will be used to determine
1067      // what level of debuggin will be established
1068      d_chip_debug = (debug & CHIP_ON) > 0 ? 1 : 0;
1069      d_pack_debug = (debug & PACKET_ON) > 0 ? 1 : 0;
1070      d_usrp_debug = (debug & USRP_ON) > 0 ? 1 : 0;
1071    }
```

```
1072
1073        DebugType
1074        preamble_sink_impl::get_debug() const
1075        {
1076          return d_debug;
1077        }
1078
1079        void
1080        preamble_sink_impl::set_crc(const CRC &crc)
1081        {
1082          d_crc = crc;
1083
1084          d_crc_set = (crc & CRC_ONLY) > 0 ? 1 : 0;
1085        }
1086
1087        void
1088        preamble_sink_impl::set_save_stats_switch(const SAVE &save_stats_switch)
1089        {
1090          d_save_stats_switch = save_stats_switch;
1091
1092          d_save_switch_set = (save_stats_switch > 0) ? 1 : 0;
1093        }
1094
1095        void
1096        preamble_sink_impl::set_save_stats_file(const std::string &save_stats_file)
1097        {
1098          d_save_stats_file = save_stats_file;
1099        }
1100
1101        SAVE
1102        preamble_sink_impl::get_save_stats_switch() const
1103        {
1104          return d_save_stats_switch;
1105        }
1106
1107        std::string
1108        preamble_sink_impl::get_save_stats_file() const
1109        {
1110          return d_save_stats_file;
1111        }
1112
1113
1114        CRC
1115        preamble_sink_impl::get_crc() const
1116        {
1117          return d_crc;
1118        }
1119
1120        uint16_t
1121        preamble_sink_impl::crc16(const char *buf, const int &len)
1122        {
1123          uint16_t crc = 0;
1124
1125          for(int i = 0; i < len; i++) {
```

```
1126            for(int k = 0; k < 8; k++) {
1127              int input_bit = (!!(buf[i] & (1 << k)) ^ (crc & 1));
1128              crc = crc >> 1;
1129              if(input_bit) {
1130                crc ^= (1 << 15);
1131                crc ^= (1 << 10);
1132                crc ^= (1 <<  3);
1133              }
1134            }
1135          }
1136
1137          return std::move(crc);
1138        }
1139
1140        void
1141        preamble_sink_impl::clear_stream()
1142        {
1143          d_msg_stream.str(std::string());
1144        }
1145
1146        void
1147        preamble_sink_impl::vector_print(const std::string &label,
1148                            const std::vector<int> &input)
1149        {
1150            if(input.empty())
1151            {
1152              fprintf(stderr, "No %s Detected\n", label.c_str()), fflush(stderr);
1153            }else
1154            {
1155              fprintf(stderr, "%s Detected at : ", label.c_str());
1156              for(auto i : input)
1157              {
1158                fprintf(stderr, "%d ", i);
1159              }
1160              fprintf(stderr, "\n"), fflush(stderr);
1161            }
1162        }
1163
1164        std::tuple<dna_buffer, bool>
1165        preamble_sink_impl::normalize_preamble(const dna_buffer &buffer,
1166                                               const int &max_return_size,
1167                                               const float &burst_trigger)
1168        {
1169          dna_buffer position_adjusted_vector;
1170          float absolute_magnitude = 0.0f;
1171          int absolute_magnitude_location = 0;
1172          int burst_trigger_location = 0;
1173          float temp_magnitude = 0;
1174          bool preamble_processed = false;
1175
1176          /*********************************************************
1177           Add Proper filter_burst Burst Detector Down the Road!!!!!
1178           *********************************************************/
1179
```

```
1180        // first step is to go through and find the min/max of the burst
1181        for(int c = 0; c < buffer.get_sample_length(); c++)
1182        {
1183          temp_magnitude = std::fabs(buffer[c]);
1184          if(temp_magnitude > absolute_magnitude)
1185          {
1186            absolute_magnitude = temp_magnitude;
1187            absolute_magnitude_location = c;
1188          }
1189        }
1190
1191        // then we divide by the largest magnitude to normalize the burst
1192        // if the signal is pure nose, then it's goig to return a burst of
1193        // pure noise
1194        bool trigger_set = false;
1195        for(int c = 0; c < buffer.get_sample_length(); c++)
1196        {
1197          temp_magnitude = std::fabs(buffer[c]);
1198          position_adjusted_vector.append_buffer_data(buffer[c]);
1199
1200          //need a flag to ensure loop doesn't keep modifing burst point
1201          if((temp_magnitude/absolute_magnitude >= burst_trigger) && (trigger_set == false))
1202          {
1203            trigger_set = true;
1204            burst_trigger_location = c;
1205          }
1206        }
1207
1208        int buffer_stop_element = d_phy_802_15_4.get_preamble_len_samples() + // 640 samples for SHR @4MS/s
1209                                  burst_trigger_location;
1210
1211        int zero_buffer_length = 0;
1212        if((buffer_stop_element + 1) > position_adjusted_vector.get_sample_length())
1213        {
1214          //case where the preamble is not available because it's index is beyond the
1215          //current buffers max
1216          position_adjusted_vector.unset_buffer();
1217          position_adjusted_vector.insert_rear_spacing(max_return_size);
1218
1219        }else{
1220          // case where we have more than enough samples to capture the preambe
1221
1222          // first we're going to remove the elements beyond the preamble location, then
1223          // we're going to remove the front where it will most likely be noise
1224          position_adjusted_vector.erase_buffer_range(buffer_stop_element, position_adjusted_vector.get_sample_length() - 1);
1225          position_adjusted_vector.erase_buffer_range(0, burst_trigger_location - 1);
1226
1227          // Afterwards we will set the remainder of the input vector to zero and returned
1228          // the normalized and non-normalized shifted preamble data
1229          zero_buffer_length = max_return_size - position_adjusted_vector.get_sample_length();
1230          position_adjusted_vector.insert_rear_spacing(zero_buffer_length);
1231          preamble_processed = true;
1232        }
1233
```

```
1234        return std::move(std::make_tuple(position_adjusted_vector, preamble_processed));
1235      }
1236
1237      std::tuple<dna_buffer,int>
1238      preamble_sink_impl::filter_burst(const dna_buffer & buffer, const int &filter_taps)
1239      {
1240        // First, we need to generate the averaging filter taps by creating a vector
1241        // that's the length of the input of filter taps with each tap weighted 1/filter_taps
1242        std::vector<float> filter;
1243        for(int c = 0; c < filter_taps; c++)
1244        {
1245          filter.push_back(1.0f/filter_taps);
1246        }
1247
1248        // these two values will be used to keep track
1249        // of the maximum magnitude while the signal is being filtered
1250        float absolute_max_value = 0.0f;
1251        float temp_max_value = 0.0f;
1252        int absolute_max_value_position = 0;
1253
1254        // the length of a discrete signal after convolution is the sum of the two signals less
1255        // one element
1256        std::vector<float> filtered_burst;
1257        float burst_sum = 0.0f;
1258
1259        for(int i = 0; i < buffer.get_sample_length(); i++)
1260        {
1261          burst_sum = 0.0f;
1262          for(int j = 0; j < filter_taps; j++)
1263          {
1264            if(((i - j) > 0) && (i >= (filter_taps - 1)))
1265            {
1266              burst_sum += std::fabs(buffer[i - j])*filter[j];
1267
1268            }
1269          }
1270          filtered_burst.push_back(burst_sum);
1271        }
1272
1273      }
```

D.1.2 Packet Sink XML GRC Code.

```
1  <?xml version="1.0"?>
2  <block>
3    <name>preamble_sink</name>
4    <key>ieee802_15_4_preamble_sink</key>
5    <category>[ieee802_15_4]</category>
6    <import>import ieee802_15_4</import>
7    <make>ieee802_15_4.preamble_sink($samp_rate, $threshold, $buffer, $burst_trigger,
8                                     $debug, $crc, $save_switch, $save_file)</make>
9      <param>
```

```
10          <name>Samp rate</name>
11          <key>samp_rate</key>
12          <type>float</type>
13        </param>
14        <param>
15          <name>Chip Error Threshold Max</name>
16          <key>threshold</key>
17          <type>int</type>
18        </param>
19
20        <param>
21          <name>Buffer Length</name>
22          <key>buffer</key>
23          <type>int</type>
24        </param>
25
26        <param>
27          <name>Burst Trigger Percentage</name>
28          <key>burst_trigger</key>
29          <type>float</type>
30        </param>
31        <param>
32          <name>CRC</name>
33          <key>crc</key>
34          <type>enum</type>
35          <option>
36            <name>ALL_DATA</name>
37            <key>0</key>
38          </option>
39          <option>
40            <name>CRC_ONLY</name>
41            <key>1</key>
42          </option>
43        </param>
44        <param>
45          <name>Save Stats?</name>
46          <key>save_switch</key>
47          <type>enum</type>
48          <option>
49            <name>NO</name>
50            <key>0</key>
51          </option>
52          <option>
53            <name>YES</name>
54            <key>1</key>
55          </option>
56        </param>
57        <param>
58          <name>Default Stats Name/Location</name>
59          <key>save_file</key>
60          <type>file_save</type>
61        </param>
62        <param>
63          <name>Debug</name>
```

```
    <key>debug</key>
    <type>enum</type>
    <option>
      <name>ALL_OFF</name>
      <key>0</key>
    </option>
    <option>
      <name>CHIP_ON</name>
      <key>1</key>
    </option>
    <option>
      <name>PACKET_ON</name>
      <key>2</key>
    </option>
    <option>
      <name>USRP_ON</name>
      <key>4</key>
    </option>
    <option>
      <name>CHIP_PACKET_ON</name>
      <key>3</key>
    </option>
    <option>
      <name>CHIP_USRP_ON</name>
      <key>5</key>
    </option>
    <option>
      <name>PACKET_USRP_ON</name>
      <key>6</key>
    </option>
    <option>
      <name>ALL_ON</name>
      <key>7</key>
    </option>
  </param>
  <sink>
    <name>in</name>
    <type>float</type>
  </sink>
  <sink>
    <name>in</name>
    <type>complex</type>
  </sink>
  <source>
    <name>out</name>
    <type>message</type>
  </source>
  <source>
    <name>preamble_out</name>
    <type>complex</type>
  </source>
  <source>
    <name>usrp_passthrough</name>
    <type>complex</type>
```

```
118     </source>
119 </block>
```

D.2 Dna detector ccf Block Source Code

D.2.1 Dna detector ccf C++ Code.

```
1  /*************************************************************************************************************************
       ***
2   *preamble_sink class
3  *************************************************************************************************************************
       **/
4  /* -*- c++ -*- */
5  /*
6   * Copyright 2018 gr-ieee802_15_4 author.
7   *
8   * This is free software; you can redistribute it and/or modify
9   * it under the terms of the GNU General Public License as published by
10  * the Free Software Foundation; either version 3, or (at your option)
11  * any later version.
12  *
13  * This software is distributed in the hope that it will be useful,
14  * but WITHOUT ANY WARRANTY; without even the implied warranty of
15  * MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the
16  * GNU General Public License for more details.
17  *
18  * You should have received a copy of the GNU General Public License
19  * along with this software; see the file COPYING.  If not, write to
20  * the Free Software Foundation, Inc., 51 Franklin Street,
21  * Boston, MA 02110-1301, USA.
22  */
23
24
25 #ifndef INCLUDED_IEEE802_15_4_DNA_DETECTOR_CCF_H
26 #define INCLUDED_IEEE802_15_4_DNA_DETECTOR_CCF_H
27
28 #include <ieee802_15_4/api.h>
29 #include <gnuradio/block.h>
30 #include <string>
31 #include "preamble_sink.h"
32
33 namespace gr {
34   namespace ieee802_15_4 {
35     /*!
36     * SWITCH is a simple on/off enum option
37     */
38     enum SWITCH{
39       OFF = 0,
40       ON = 1
41     };
```

```
42  /*!
43  *  Class: dna_detector
44  *  Author: Cruz, Frankie
45  *  Description: the class is calculates which emmiter is being received
46  *               by performing rf-dna analysis and outputting the results
47  *               to a histogram via msg passing and reduces the ammount
48  *               of output data bursts passed in by reducing the "dead"
49  *               space in between
50  *  Generated: Mon Dec 3 17:30:12 2018
51  *  Modified: Sat Feb 2 9:00:28 2018
52  *  Build Version: 1.11
53  *  Changes: -Cleaned code up a bit
54  */
55  class IEEE802_15_4_API dna_detector_ccf : virtual public gr::block
56  {
57   public:
58    typedef boost::shared_ptr<dna_detector_ccf> sptr;
59    /*!
60     * param fingerprints is the number of emmiters that will be analyzed
61     * param dna_row_size is the row size of the imported rfdna fingerprints
62     * param dna_column_size is the column size of the imported rfdna fingerprints
63     * param dna_region_num is the number of regions used for rfdna fingerprints
64     * param samp_rate is the sample rate of the system
65     * param fingerprint_filename is the filename the user picks to store fingerprints
66     * param fingerprint_save_switch is the on/off to store fingerprints
67     * param class_matrix_filename is the trained classification file to load into a matrix
68     * param means_matrix_filename is the trained device means file to load into a matrix
69     * param class_matrix_load_switch is the on/off to load the DNA file
70     * param norm_vector_filename is the scaling multiplier for fingerprints generated by trained data
71     * param xoffset_vector_filename is an offset that has to be applied to the generated fingerprints
72     * param save_stats_switch is the on/off to store running stats info (note: write can be behind)
73     * param save_dna_results is the on/off to store the result of the fingerprint and DNA matrix
74     */
75    static sptr make(int devices, int dna_row_size, int dna_col_size, int dna_region_num,
76                     DebugType debug, float samp_rate, std::string fingerprint_filename,
77                     SWITCH fingerprint_save_switch, std::string class_matrix_filename,
78                     std::string means_matrix_filename, std::string norm_vector_filename,
79                     std::string xoffset_vector_filename, SWITCH class_matrix_load_switch,
80                     SWITCH save_stats_switch, SWITCH save_dna_results);
81
82    virtual void set_devices(const int &devices) = 0;
83    virtual void set_dna_row_size(const int &row_size) = 0;
84    virtual void set_dna_column_size(const int &col_size) = 0;
85    virtual void set_dna_region_num(const int &region_num) = 0;
86    virtual void set_debug(const DebugType &debug) = 0;
87    virtual void set_dna_fingerprint_filename(const std::string &fingerprint_filename) = 0;
88    virtual void set_dna_fingerprint_save_switch(const SWITCH &fingerprint_save_switch) = 0;
89    virtual void set_dna_classification_matrix_filename(const std::string &class_matrix_filename) = 0;
90    virtual void set_dna_means_matrix_filename(const std::string &means_matrix_filename) = 0;
91    virtual void set_dna_classification_load_switch(const SWITCH &class_matrix_load_switch) = 0;
92    virtual void set_save_stats_switch(const SWITCH &save_stats_switch) = 0;
93    virtual void set_save_dna_results_switch(const SWITCH &save_dna_results_switch) = 0;
94    virtual void set_samp_rate(const float &samp_rate) = 0;
95    virtual void set_dna_norm_vector_filename(const std::string &norm_vector_filename) = 0;
```

```
96          virtual void set_dna_xoffset_vector_filename(const std::string &xoffset_vector_filename) = 0;
97
98          virtual int get_devices() const = 0;
99          virtual int get_dna_row_size() const = 0;
100         virtual int get_dna_column_size() const = 0;
101         virtual int get_dna_region_num() const = 0;
102         virtual DebugType get_debug() const = 0;
103         virtual std::string get_dna_fingerprint_filename() const = 0;
104         virtual SWITCH get_dna_fingerprint_save_switch() const = 0;
105         virtual std::string get_dna_classification_matrix_filename() const = 0;
106         virtual std::string get_dna_means_matrix_filename() const = 0;
107         virtual SWITCH get_dna_classification_load_switch() const = 0;
108         virtual SWITCH get_save_stats_switch() const = 0;
109         virtual SWITCH get_save_dna_results_switch() const = 0;
110         virtual float get_samp_rate() const = 0;
111         virtual std::string get_dna_norm_vector_filename() const = 0;
112         virtual std::string get_dna_xoffset_vector_filename() const = 0;
113       };
114
115   } // namespace ieee802_15_4
116 } // namespace gr
117 #endif /* INCLUDED_IEEE802_15_4_DNA_DETECTOR_CCF_H */
118
119 /*************************************************************************************************************************
        ***
120  *preamble_sink_impl.h impletation class definitions
121 *************************************************************************************************************************
        **/
122 /* -*- c++ -*- */
123 /*
124  * Copyright 2018 gr-ieee802_15_4 author.
125  *
126  * This is free software; you can redistribute it and/or modify
127  * it under the terms of the GNU General Public License as published by
128  * the Free Software Foundation; either version 3, or (at your option)
129  * any later version.
130  *
131  * This software is distributed in the hope that it will be useful,
132  * but WITHOUT ANY WARRANTY; without even the implied warranty of
133  * MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the
134  * GNU General Public License for more details.
135  *
136  * You should have received a copy of the GNU General Public License
137  * along with this software; see the file COPYING.  If not, write to
138  * the Free Software Foundation, Inc., 51 Franklin Street,
139  * Boston, MA 02110-1301, USA.
140  */
141
142 #ifndef INCLUDED_IEEE802_15_4_DNA_DETECTOR_CCF_IMPL_H
143 #define INCLUDED_IEEE802_15_4_DNA_DETECTOR_CCF_IMPL_H
144
145 #include <ieee802_15_4/dna_detector_ccf.h>
146 #include "preamble_sink_impl.h" //included to add class types stored i.e. dna_buffer packets
147
```

```
148  // Boost matrix libraries
149  #include <boost/numeric/ublas/vector.hpp>
150  #include <boost/numeric/ublas/matrix.hpp>
151  #include <boost/numeric/ublas/operation.hpp>
152  #include <boost/numeric/ublas/operations.hpp>
153  #include <boost/numeric/ublas/io.hpp>
154
155  // Boost Stats Libraries
156  #include <boost/math/distributions.hpp>
157  #include <boost/bind.hpp>
158  #include <boost/ref.hpp>
159  #include <boost/accumulators/accumulators.hpp>
160  #include <boost/accumulators/statistics/stats.hpp>
161  #include <boost/accumulators/statistics/mean.hpp>
162  #include <boost/accumulators/statistics/moment.hpp>
163  #include <boost/accumulators/statistics/variance.hpp>
164  #include <boost/accumulators/statistics/skewness.hpp>
165  #include <boost/accumulators/statistics/kurtosis.hpp>
166
167  // Eigen Matrix libraries
168  #include <eigen3/Eigen/Dense>
169
170  //std libraries
171  #include <sstream>
172  #include <iostream>
173  #include <fstream>
174  #include <memory>
175  #include <cmath>
176  #include <iomanip>
177  #include <ctime>
178
179  namespace gr {
180    namespace ieee802_15_4 {
181
182      //shorthand syntax simplifier for calling Eignen complex matricies and vectors
183      template<class T>
184      using EigMat = Eigen::Matrix<T, Eigen::Dynamic, Eigen::Dynamic>; //EigRow is a N x 1 matrix shorthand
185      template<class T>
186      using EigColVec = Eigen::Matrix<T, Eigen::Dynamic, 1>; //EigColVec is a N x 1 vector shorthand
187      template<class T>
188      using EigRowVec = Eigen::Matrix<T, 1, Eigen::Dynamic>; //EigRowVec is a 1 x M vector shorthand
189
190      //shorthand syntax for calling boost specific matricies and vectors
191      template<class V>
192      using BoostMat = boost::numeric::ublas::matrix<V>; //specifiy N x M at generation
193      template<class V>
194      using BoostVec = boost::numeric::ublas::vector<V>; //specify vector length at generation
195
196      // using the accumulator namespace and dna_marker
197      // alias provide some flexibility on the data being analyzed
198      // and shortening the ammount of code to type....
199      using namespace boost::accumulators;  // shortening boost call
200      template<class X>
```

```
201     using dna_marker = boost::accumulators::accumulator_set<X, features<tag::count, tag::mean(immediate), tag::variance(
            immediate), tag::skewness, tag::kurtosis>>;
202
203     class dna_detector_ccf_impl : public dna_detector_ccf
204     {
205      private:
206       enum{SEARCHING, DETECTED, FINGERPRINT} d_state; // keep track of what state we're in
207
208       int d_devices = 5;                    // number of devices/fingerprints input for analysis
209       int d_usrp_debug = 0;                      // USRP verbose output for debugging
210       int d_dna_row_size;                         // dna fingerprints row dimension
211       int d_dna_column_size;                     // dna fingerprints column dimension
212       int d_dna_region_num = 10;                  // # of fingerprint regions
213       float d_samp_rate = 4e6;                   //default sample rate
214
215       std::stringstream d_msg_stream;            // designed to handle messages string messages
216       std::stringstream d_emitter_stats_stream; // designed to save results info for each emmitters results
217       std::string d_fingerprint_filename;        // filename to save fingerprints
218       std::string d_fingerprint_stats_filename; // filename to save stats
219       std::string d_matrix_mult_results_filename; // filename to save
220       std::string d_norm_vector_filename;         // normalization vectors filename
221       std::string d_xoffset_vector_filename;       // offset vectors filename
222       SWITCH d_fingerprint_save_switch = SWITCH::OFF;  // option to save the fingerprints generated per run
223       std::string d_class_matrix_filename;              // classification matrix file name
224       std::string d_means_matrix_filename;              // means matrix file name
225       SWITCH d_class_matrix_load_switch = SWITCH::OFF; // option to load a classifier file
226       SWITCH d_save_stats_switch = SWITCH::OFF;        // option to save the generated statistics
227       SWITCH d_save_dna_results_switch = SWITCH::OFF;  // option to save dna multiplication results
228
229       //File Read & Write Modifiers
230       std::shared_ptr<file_read_impl> d_xoffset_vector_loader; // loades calculated fingerprint offsets
231       std::shared_ptr<file_read_impl> d_norm_vector_loader; // loads calculated normalization scaling vector
232       std::shared_ptr<file_read_impl> d_class_means_loader; // loads calculated means for each device generated by MATLAB
233       std::shared_ptr<file_read_impl> d_dna_loader; // loads classification matrix generated by MATLAB
234       std::shared_ptr<file_store_impl> d_dna_fingerprint_write; // for d_dna_fingerprints
235       std::shared_ptr<file_store_impl> d_stats_writer; //for statistis output file
236       std::shared_ptr<file_store_impl> d_matrix_results_writer; // stores results of multiplication matrix
237       std::shared_ptr<file_store_impl> d_dna_results_writer; //stores results of dna multiplication
238
239       DebugType d_debug = ALL_OFF;                 // debug type
240       unsigned long int d_burst_count = 0;        // burst counter(4,294,967,295 size limit)
241       unsigned long int d_fingerprints_counter = 0; // fingerprint generation counter
242       unsigned long int d_nan_counter = 0;       //keeps track of fingerprints that were not sent
243
244       ieee802_15_4_packet d_phy_802_15_4;         //contains all the class sizing functions
245
246       std::vector<unsigned long int> d_emitter_bin_counter;             // array keeping track of what devices were identified
247       std::vector<gr_complex> d_current_detected_preamble;
248       std::vector<float> d_dna_results;
249       std::vector<float> d_dna_fingerprints;       // calculated fingerprints from detected preamble
250       EigMat<float> d_dna_matrix;            // classification matrix generated from matlab
251       EigMat<float> d_class_means_matrix; // device classification means generated from matlab
252       EigRowVec<float> d_norm_vector;    // normalization vector to scale incomming fingerprint by
253       EigRowVec<float> d_xoffset_vector; // offset vector to adjust collected fingerprints
```

```
254
255         public:
256          dna_detector_ccf_impl(int devices, int dna_row_size, int dna_column_size, int dna_region_num,
257                                DebugType debug, float samp_rate, std::string fingerprint_filename,
258                                SWITCH fingerprint_save_switch, std::string class_matrix_filename,
259                                std::string means_matrix_filename, std::string norm_vector_filename,
260                                std::string xoffset_vector_filename, SWITCH class_matrix_load_switch,
261                                SWITCH save_stats_switch, SWITCH save_dna_results_switch);
262
263          ~dna_detector_ccf_impl();
264
265          // Where all the action really happens
266          void forecast (int noutput_items, gr_vector_int &ninput_items_required);
267
268          int general_work(int noutput_items,
269               gr_vector_int &ninput_items,
270               gr_vector_const_void_star &input_items,
271               gr_vector_void_star &output_items);
272
273          // state functions to process data
274          void burst_search();
275          void burst_detect();
276          void burst_fingerprint();
277
278          // publicly available setters
279          void set_devices(const int & devices);          //set the # of devices
280          void set_dna_row_size(const int &dna_row_size); // set the row size of dna matrix, ie N of N x M
281          void set_dna_column_size(const int &dna_column_size); // set the column size of the dna matrix, ie M of N x M
282          void set_dna_region_num(const int &dna_region_num);  // set the number of regions used in fingerprinting
283          void set_debug(const DebugType &debug);
284          void set_dna_fingerprint_filename(const std::string &fingerprint_filename);
285          void set_dna_fingerprint_save_switch(const SWITCH &fingerprint_save_switch);
286          void set_dna_classification_matrix_filename(const std::string &class_matrix_filename);
287          void set_dna_means_matrix_filename(const std::string &mean_matrix_filename);
288          void set_dna_classification_load_switch(const SWITCH &class_matrix_load_switch);
289          void set_save_stats_switch(const SWITCH &save_stats_switch);
290          void set_save_dna_results_switch(const SWITCH &save_dna_results_switch);
291          void set_samp_rate(const float &samp_rate);
292          void set_dna_norm_vector_filename(const std::string &norm_vector_filename);
293          void set_dna_xoffset_vector_filename(const std::string &xoffset_vector_filename);
294          void clear_stream(); // shorthand way to clear d_msg_stream via stackoverflow.com
295
296          //publicly available getters
297          int get_devices() const;
298          int get_dna_row_size() const;
299          int get_dna_column_size() const;
300          int get_dna_region_num() const;
301          DebugType get_debug() const;
302          std::string get_dna_fingerprint_filename() const;
303          SWITCH get_dna_fingerprint_save_switch() const;
304          std::string get_dna_classification_matrix_filename() const;
305          std::string get_dna_means_matrix_filename() const;
306          SWITCH get_dna_classification_load_switch() const;
307          SWITCH get_save_stats_switch() const;
```

```
308         SWITCH get_save_dna_results_switch() const;
309         float get_samp_rate() const;
310         std::string get_dna_norm_vector_filename() const;
311         std::string get_dna_xoffset_vector_filename() const;
312
313         //Work Functions
314         float constrain_angle(const float &angle);                          // puts angle from -pi to pi from stackoverflow.com
315         float angle_conv(const float &angle);                               // converts angle from -2pi to 2pi from stackoverflow.
                com
316         float angle_diff(const float &angle_a, const float &angle_b); // ensures a way to handle pi == -pi from stackoverflow.com
317         float unwrap_phase(const float &prev_angle, const float &current_angle); // unwrap function from stackoverflow.com
318         std::vector<float> calculate_fingerprints(const std::vector<gr_complex> &burst); // the input burst will return the est
                device
319
320         //make_subregion will return a subretion consisting of the amplitude, phse, and frequency of the provided samples
321         //likewise, the amplitude, phase, and frequency sub-sections will consist of 3 samples each of the calculated
322         //varriance, skewness, and kurtosis
323         std::vector<float> make_subregion(const std::vector<gr_complex> &sub_region);
324
325         // fingerprint_emmiter will take in the calculated fingerprints statistics and
326         // will multiply the vector with the loaded fingerprint data
327         std::vector<float> fingerprint_emitter(const std::vector<float> &fingerprint);
328
329
330       };
331     } // namespace ieee802_15_4
332   } // namespace gr
333   #endif /* INCLUDED_IEEE802_15_4_DNA_DETECTOR_CCF_IMPL_H */
334
335   /*************************************************************************************************************************
          ***
336    *dna_detector_ccf_imph.cc impletation source code
337   *************************************************************************************************************************
          **/
338   /* -*- c++ -*- */
339   /*
340    * Copyright 2018 gr-ieee802_15_4 author.
341    *
342    * This is free software; you can redistribute it and/or modify
343    * it under the terms of the GNU General Public License as published by
344    * the Free Software Foundation; either version 3, or (at your option)
345    * any later version.
346    *
347    * This software is distributed in the hope that it will be useful,
348    * but WITHOUT ANY WARRANTY; without even the implied warranty of
349    * MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the
350    * GNU General Public License for more details.
351    *
352    * You should have received a copy of the GNU General Public License
353    * along with this software; see the file COPYING.  If not, write to
354    * the Free Software Foundation, Inc., 51 Franklin Street,
355    * Boston, MA 02110-1301, USA.
356    */
357
```

```
358 #ifdef HAVE_CONFIG_H
359 #include "config.h"
360 #endif
361
362 #include <gnuradio/io_signature.h>
363 #include "dna_detector_ccf_impl.h"
364
365 namespace gr {
366   namespace ieee802_15_4 {
367     dna_detector_ccf::sptr
368     dna_detector_ccf::make(int devices, int dna_row_size, int dna_column_size, int dna_region_num,
369                            DebugType debug, float samp_rate, std::string fingerprint_filename,
370                            SWITCH fingerprint_save_switch, std::string class_matrix_filename,
371                            std::string means_matrix_filename, std::string norm_vector_filename,
372                            std::string xoffset_vector_filename, SWITCH class_matrix_load_switch,
373                            SWITCH save_stats_switch, SWITCH save_dna_results_switch)
374     {
375       return gnuradio::get_initial_sptr
376         (new dna_detector_ccf_impl(devices, dna_row_size, dna_column_size, dna_region_num,
377                                    debug, samp_rate, fingerprint_filename,
378                                    fingerprint_save_switch, class_matrix_filename,
379                                    means_matrix_filename, norm_vector_filename,
380                                    xoffset_vector_filename, class_matrix_load_switch,
381                                    save_stats_switch, save_dna_results_switch));
382     }
383
384     /*
385      * The private constructor
386      */
387     dna_detector_ccf_impl::dna_detector_ccf_impl(int devices, int dna_row_size, int dna_column_size, int dna_region_num,
388                                                  DebugType debug, float samp_rate, std::string fingerprint_filename,
389                                                  SWITCH fingerprint_save_switch, std::string class_matrix_filename,
390                                                  std::string means_matrix_filename, std::string norm_vector_filename,
391                                                  std::string xoffset_vector_filename, SWITCH class_matrix_load_switch,
392                                                  SWITCH save_stats_switch, SWITCH save_dna_results_switch)
393       : gr::block("dna_detector_ccf",
394               gr::io_signature::make(1, 1, sizeof(gr_complex)),
395               gr::io_signature::make(0, 0, 0))
396     {
397       d_devices = devices;
398       d_dna_row_size = dna_row_size;
399       d_dna_column_size = dna_column_size;
400       d_dna_region_num = dna_region_num;
401       set_debug(debug);
402       d_samp_rate = samp_rate;
403       d_phy_802_15_4.set_sample_rate(samp_rate);
404       d_fingerprint_filename = fingerprint_filename;
405       d_fingerprint_save_switch = fingerprint_save_switch;
406       d_class_matrix_filename = class_matrix_filename;
407       d_class_matrix_load_switch = class_matrix_load_switch;
408       d_save_stats_switch = save_stats_switch;
409       d_save_dna_results_switch = save_dna_results_switch;
410       d_means_matrix_filename = means_matrix_filename;
411       d_norm_vector_filename = norm_vector_filename;
```

```
412         d_xoffset_vector_filename = xoffset_vector_filename;
413
414         // vector will be used to keep track of what device
415         // "bin's" were detected
416         for(int c = 0; c < devices; c++)
417         {
418           d_emitter_bin_counter.push_back(0);
419         }
420         std::cout << "\nSample Rate on DNA Detector set to " << samp_rate << std::endl;
421
422         // If the user doesn't load any dna data,
423         // the  data will automatically be set
424         // as an Identity matrix
425         if(d_class_matrix_load_switch == SWITCH::ON)
426         {
427           // empty vectors will be used to store the loaded data
428           // the eigen map function will handle mapping the data
429           // as a vector/matrix as appropriate
430           std::vector<float> data_vector(dna_row_size * dna_column_size,0.0f);
431           std::vector<float> means_vector(devices * dna_column_size, 0.0f);
432           std::vector<float> norm_vector(dna_row_size,0.0f);
433           std::vector<float> offset_vector(dna_row_size,0.0f);
434
435           d_dna_loader = std::make_shared<file_read_impl>(sizeof(float), class_matrix_filename.c_str(), false);
436           d_dna_loader->read_data(dna_row_size*dna_column_size, (void *)data_vector.data());
437           std::cout << "\n" << d_class_matrix_filename << " classification matrix loaded ";
438           std::cout << data_vector.size() << "-items.\n" << std::endl;
439           d_dna_matrix = EigMat<float>::Map(data_vector.data(),
440                                             dna_row_size,
441                                             dna_column_size);
442           std::cout << "\n" << dna_row_size << " by " << dna_column_size << " loaded.\n" << std::endl;
443
444           d_class_means_loader = std::make_shared<file_read_impl>(sizeof(float), means_matrix_filename.c_str(), false);
445           d_class_means_loader->read_data(devices*dna_column_size, (void *)means_vector.data());
446           std::cout << "\n" << d_means_matrix_filename << " means matrix loaded ";
447           std::cout << data_vector.size() << "-items.\n" << std::endl;
448           d_class_means_matrix = EigMat<float>::Map(means_vector.data(),
449                                                     devices,
450                                                     dna_column_size);
451           std::cout << "\n" << devices << " by " << dna_column_size << " loaded.\n" << std::endl;
452
453           d_norm_vector_loader = std::make_shared<file_read_impl>(sizeof(float), norm_vector_filename.c_str(), false);
454           d_norm_vector_loader->read_data(dna_row_size, (void *)norm_vector.data());
455           std::cout << "\n" << d_norm_vector_filename << " normalization vector loaded ";
456           std::cout << norm_vector.size() << "-items.\n" << std::endl;
457           d_norm_vector = EigRowVec<float>::Map(norm_vector.data(), 1, dna_row_size);
458           std::cout << "\n1 by " << dna_row_size << " loaded.\n" << std::endl;
459
460           d_xoffset_vector_loader = std::make_shared<file_read_impl>(sizeof(float), xoffset_vector_filename.c_str(), false);
461           d_xoffset_vector_loader->read_data(dna_row_size, (void *)offset_vector.data());
462           std::cout << "\n" << d_xoffset_vector_filename << " xoffset vector loaded ";
463           std::cout << offset_vector.size() << "-items.\n" << std::endl;
464           d_xoffset_vector = EigRowVec<float>::Map(offset_vector.data(), 1, dna_row_size);
465           std::cout << "\n1 by " << dna_row_size << " loaded.\n" << std::endl;
```

```
466
467         }else{
468           std::cout << "\nClassification data matrix wasn't loaded.  A " << dna_row_size << " by " << dna_column_size << "
                  identity matrix loaded instead." << "\n";
469           std::cout << "A pure " << dna_row_size << " by 1 fingerprint passthrough will occur\n" << std::endl;
470           d_dna_matrix = Eigen::MatrixXf::Identity(dna_row_size, dna_row_size);
471
472           std::cout << "\nMeans data matrix wasn't loaded.  A " << devices << " by " << dna_column_size << " identity matrix
                  loaded instead." << "\n";
473           std::cout << "A " << devices << " by " << dna_column_size << " identity matrix will be loaded instead.\n" << std::endl;
474           d_class_means_matrix = Eigen::MatrixXf::Identity( devices, dna_column_size);
475
476           std::cout << "\nNormalization data vector wasn't loaded.  A 1 by " << dna_row_size << " ones vector loaded instead." <<
                  "\n";
477           std::cout << "A 1 by " << dna_row_size << " ones vector will be loaded instead.\n" << std::endl;
478           d_norm_vector = Eigen::MatrixXf::Ones( 1, dna_row_size);
479
480           std::cout << "\nXOffset data vector wasn't loaded.  A 1 by " << dna_row_size << " ones vector loaded instead." << "\n";
481           std::cout << "A 1 by " << dna_row_size << " ones vector will be loaded instead.\n" << std::endl;
482           d_xoffset_vector = Eigen::MatrixXf::Ones( 1, dna_row_size);
483
484         }
485
486         // The collected fingerprint data will continuously be
487         // stacked on the end of the file until the program is over
488         if(d_fingerprint_save_switch == SWITCH::ON)
489         {
490           std::cout << "\nGenerated fingerprints will be saved as binary data to " << d_fingerprint_filename << "\n" << std::endl;
491           d_dna_fingerprint_write = std::make_shared<file_store_impl>(sizeof(float), d_fingerprint_filename.c_str(),
492                                                                       //true, true);
493                                                                       true, false);
494         }
495
496         // The output dna analysis will be saved just like the
497         // fingerprints but with "_dna_results" appended to
498         // the default filename
499         if(d_save_dna_results_switch == SWITCH::ON)
500         {
501           std::string temp = fingerprint_filename + "_dna_results";
502           std::cout << "\nGenerated dna_results will be saved as binary data to " << temp << "\n" << std::endl;
503           d_dna_results_writer = std::make_shared<file_store_impl>(sizeof(float), temp.c_str(), true,false);//true, true);
504         }
505
506         // Option to collect the statistics generated
507         // for the generated fingerprints and results
508         if( d_save_stats_switch == SWITCH::ON)
509         {
510           // from stackoverflow.com, just a quick way to append time/date to a filename
511           auto t = std::time(nullptr);
512           auto tm = *std::localtime(&t);
513
514           // stat's result file load/creation
515           d_msg_stream << d_fingerprint_filename << "_stats_" << std::put_time(&tm, "%d%b%y_%R") << ".txt";
516           d_fingerprint_stats_filename.append(d_msg_stream.str());
```

```
517         clear_stream();
518         std::cout << "\nGenerated stats will be saved to " << d_fingerprint_stats_filename << ".\n" << std::endl;
519         d_stats_writer = std::make_shared<file_store_impl>(sizeof(char), d_fingerprint_stats_filename.c_str(),
520                                                           false, false);
521         d_msg_stream << "\n================================================================================" << "\n";
522         d_msg_stream <<  "Collection started on " << std::put_time(&tm, "%F_%T");
523         d_msg_stream <<  "\nSample Rate at " << samp_rate;
524         d_msg_stream <<  "\n" << d_dna_region_num << " regions of interest for fingerprints = " << dna_region_num * 9 << "
                samples per fingerprint";
525         d_msg_stream <<  "\nPreamble sample length at " << samp_rate << " Samp/sec is " << d_phy_802_15_4.
                get_preamble_len_samples();
526         d_msg_stream <<  "\nPacket sample length at " << samp_rate << " Samp/sec is " << d_phy_802_15_4.get_packet_len_samples()
                ;
527         d_msg_stream << "\n================================================================================" << "\n";
528         d_stats_writer->store_data(d_msg_stream.str().size(), (void*)d_msg_stream.str().c_str());
529         clear_stream();
530
531
532         // matrix result file load/creation
533         d_msg_stream << d_fingerprint_filename << "_matrix_mult_" << std::put_time(&tm, "%d%b%y_%R") << ".txt";
534         d_matrix_mult_results_filename.append(d_msg_stream.str());
535         clear_stream();
536         d_matrix_results_writer = std::make_shared<file_store_impl>(sizeof(char), d_matrix_mult_results_filename.c_str(),
537                                                                     false, false);
538         std::cout << "\nGenerated multiplication results will be saved to " << d_matrix_mult_results_filename << ".\n" << std::
                endl;
539
540
541         d_msg_stream << "\n================================================================================" << "\n";
542         d_msg_stream <<  "Collection started on " << std::put_time(&tm, "%F_%T");
543         d_msg_stream <<  "\nSample Rate at " << samp_rate << "\n";
544         d_msg_stream <<  "\nPreamble sample length at " << samp_rate << " Samp/sec is " << d_phy_802_15_4.
                get_preamble_len_samples();
545         d_msg_stream <<  "\nPacket sample length at " << samp_rate << " Samp/sec is " << d_phy_802_15_4.get_packet_len_samples()
                ;
546         d_msg_stream <<  "\n" << d_dna_region_num << " regions of interest for fingerprints = " << dna_region_num * 9 << "
                samples per fingerprint";
547         d_msg_stream << "\nLoaded Classification Matrix Dimensions: " << d_dna_matrix.rows() << " by " << d_dna_matrix.cols() <<
                 "\n";
548         d_msg_stream << d_dna_matrix << "\n";
549         d_msg_stream << "\n================================================================================" << "\n";
550         d_msg_stream << "Loaded Means Matrix Dimensions: " << d_class_means_matrix.rows() << " by " << d_class_means_matrix.cols
                () << "\n";
551         d_msg_stream << d_class_means_matrix << "\n";
552         d_msg_stream << "\n================================================================================" << "\n";
553         d_msg_stream << "Loaded Normalization Vector Dimensions: 1  by " << d_norm_vector.cols() << "\n";
554         d_msg_stream << d_norm_vector << "\n";
555         d_msg_stream << "\n================================================================================" << "\n";
556         d_msg_stream << "Loaded X-Offset Vector Dimensions: 1  by " << d_xoffset_vector.cols() << "\n";
557         d_msg_stream << d_xoffset_vector << "\n";
558         d_msg_stream << "\n================================================================================" << "\n";
559         d_matrix_results_writer->store_data(d_msg_stream.str().size(),(void*)d_msg_stream.str().c_str());
560     }
561
```

```
562       // Option to save DNA results
563
564       burst_search();
565       message_port_register_out(pmt::mp("dna_out"));
566     }
567
568     /*
569      * Our virtual destructor.
570      */
571     dna_detector_ccf_impl::~dna_detector_ccf_impl()
572     {
573     }
574
575     void
576     dna_detector_ccf_impl::forecast (int noutput_items, gr_vector_int &ninput_items_required)
577     {
578       ninput_items_required[0] = 2044;
579     }
580
581     int
582     dna_detector_ccf_impl::general_work (int noutput_items,
583                         gr_vector_int &ninput_items,
584                         gr_vector_const_void_star &input_items,
585                         gr_vector_void_star &output_items)
586     {
587       const gr_complex *input_bursts = (const gr_complex *) input_items[0]; // detected ieee802-15-4 bursts
588       int ninput = ninput_items[0]; // size of input burst data stream
589
590       float magnitude = 0.0f;
591
592       int burst_index = 0;
593       int sample_limit = d_phy_802_15_4.get_preamble_len_samples() + 10; //"oh crap" 10 sample buffer added
594
595       while(burst_index < ninput)
596       {
597         switch(d_state)
598         {
599           case SEARCHING:
600             //since the bursts are zero buffered and dealing with floating numbers,
601             //an exremely small floating number will be used
602             if(std::abs(input_bursts[burst_index]) > 1.0e-38f)
603             {
604               // The previous detector ensures that every burst has exactly a complex
605               // zero as thier value so all complex zero's are ignored before the
606               // preamble bursts
607               burst_detect();
608             }else{
609               burst_index++;
610             }
611             break;
612
613           case DETECTED:
614             //if(d_current_detected_preamble.get_sample_length() < sample_limit)
615             if(d_current_detected_preamble.size() < sample_limit)
```

```
616             {
617               d_current_detected_preamble.push_back(input_bursts[burst_index++]);
618             }else{
619               // filled burst will be sent to be fingerprinted
620               burst_fingerprint();
621             }
622             break;
623
624           case FINGERPRINT:
625             //put case statement in brackets because of
626             //compilation errors
627             {
628               // At this point, I need to perform RFDNA Analysis and get the fingerprint
629               // from the latest pre-amble
630               d_dna_fingerprints = calculate_fingerprints(d_current_detected_preamble);
631
632               // Here, the fingerprint will be compared against the trained
633               // data and return the euclidean distances calculated from
634               // the loaded Matlab matricies
635               d_dna_results = fingerprint_emitter(d_dna_fingerprints);
636
637               //We need to check if a NaN value is detected since it would invalidate our fingerprint
638               bool nan_found = false;
639               for(std::vector<gr_complex>::size_type i = 0; i != d_dna_fingerprints.size(); i++)
640               {
641                 if(std::isnan(d_dna_fingerprints[i]))
642                 {
643                   nan_found = true;
644                   d_nan_counter++;
645                   break;
646                 }
647               }
648
649               //Increment counters for stats
650               if(!nan_found)
651               {
652                 d_fingerprints_counter++;
653               }
654
655               // Here, the generated fingerprint will be passed on if
656               // the user has enabled saving fingerprints and they do
657               // not contain NaN's
658               if((d_fingerprint_save_switch == SWITCH::ON) && !nan_found)
659               {
660                 d_dna_fingerprint_write->store_data(d_dna_fingerprints.size(), (void*)d_dna_fingerprints.data());
661               }
662
663               // Here, the generated fingerprint will be passed on if
664               // the user has enabled saving fingerprints and they do
665               // not contain NaN's
666               if((d_save_dna_results_switch == SWITCH::ON) && !nan_found)
667               {
668                 d_dna_results_writer->store_data(d_dna_results.size(), (void*)d_dna_results.data());
669               }
```

```
670
671                 // setting the initial min to the numeric limit
672                 // of a float ensures that
673                 float min = std::numeric_limits<float>::max();
674                 int most_likely = 0;
675
676                 if(!nan_found)
677                 {
678                   for(int c = 0; c < d_devices; c++)
679                   {
680                     if(d_dna_results[c] < min)
681                     {
682                       min = d_dna_results[c];
683                       most_likely = c+1;
684                     }
685                   }
686                 }
687
688                 //Increment Emitter array
689                 d_emitter_bin_counter[most_likely - 1] += 1;
690
691                 //now I use c to pass the vector values to the histogram
692                 pmt::pmt_t dna_results = pmt::make_f32vector(d_devices,0.0);
693                 for(int i = 0; i < d_devices; i++)
694                 {
695                     pmt::f32vector_set(dna_results, i, most_likely);
696                 }
697
698                 // A message indicating which device will only be sent out
699                 // if the fingerprint generated was valid
700                 if(!nan_found)
701                 {
702                   message_port_pub(pmt::mp("dna_out"), dna_results);
703                 }
704
705                 // This if block will save the data overview of the fingerprints
706                 // in a simple to read output
707                 if(d_save_stats_switch == SWITCH::ON)
708                 {
709                   clear_stream();
710                   d_msg_stream << "\n----------------------------------------------------------------------------------------------------" <<
                           "\n";
711                   d_msg_stream << "Burst: " << d_burst_count + 1 << "\n";
712                   d_msg_stream << "Device Most Likely: " << (nan_found ? "N/A, NaN detected" : std::to_string(most_likely)) << "\n
                           ";
713                   d_msg_stream << "Device Result Value: " << (nan_found ? "NaN" : std::to_string(d_dna_results[most_likely - 1]))
                          << "\n";
714                   d_msg_stream << "Total Valid Fingerprints: " << d_fingerprints_counter << "\n";
715                   d_msg_stream << "Total Invalid Fingerprints: " << d_nan_counter << "\n";
716                   for(std::vector<unsigned long int>::size_type i = 0; i != d_emitter_bin_counter.size(); i++)
717                   {
718                     d_msg_stream << "Emitter_" << i+1 << " Count:" << d_emitter_bin_counter[i] << "\t";
719                   }
```

```
720                     d_msg_stream << "\n----------------------------------------------------------------------------------------------------" <<
                            "\n";
721                     d_stats_writer->store_data(d_msg_stream.str().size(),(void*)d_msg_stream.str().c_str());
722                   }
723
724                   // this if statement will keep track of all the math involved and results for every
725                   // fingerprint that is analyzed
726                   if(d_save_stats_switch == SWITCH::ON)
727                   {
728                     clear_stream();
729                     d_msg_stream << "\n----------------------------------------------------------------------------------------------------" <<
                            "\n";
730                     d_msg_stream << "Burst: " << d_burst_count + 1 << (nan_found ? " contains a NaN\n" : "\n");
731                     d_msg_stream << "Fingerprints: ";
732                     for(std::vector<float>::size_type i = 0; i != d_dna_fingerprints.size(); i++)
733                     {
734                       if(i < (d_dna_fingerprints.size() - 1))
735                       {
736                         d_msg_stream << d_dna_fingerprints[i] << ", ";
737                       }else{
738                         d_msg_stream << d_dna_fingerprints[i] << "\n";
739                       }
740                     }
741                     d_msg_stream << "DNA Results: ";
742                     for(std::vector<float>::size_type i = 0; i != d_dna_results.size(); i++)
743                     {
744                       if(i < (d_dna_results.size() - 1))
745                       {
746                         d_msg_stream << d_dna_results[i] << ", ";
747                       }else{
748                         d_msg_stream << d_dna_results[i] << "\n";
749                       }
750                     }
751                     d_msg_stream << "----------------------------------------------------------------------------------------------------" << "\n
                            ";
752                     d_matrix_results_writer->store_data(d_msg_stream.str().size(),(void*)d_msg_stream.str().c_str());
753                   }
754
755                   //Option to actively see the fingerprints & results comming out
756                   if((d_debug == DebugType::USRP_ON) || (d_debug == DebugType::ALL_ON))
757                   {
758                     std::cout << "\n----------------------------------------------------------------------------------------------------" << "\n
                            ";
759                     std::cout << "Fingerprint #" << d_burst_count + 1<< ": ";
760                     for(std::vector<float>::iterator c = d_dna_fingerprints.begin(); c != d_dna_fingerprints.end(); ++c)
761                     {
762                       std::cout << (*c) << ", ";
763                     }
764                     std::cout << "\nResults #" << d_burst_count + 1<< ": ";
765                     for(std::vector<float>::iterator c = d_dna_results.begin(); c != d_dna_results.end(); ++c)
766                     {
767                       std::cout << (*c) << ", ";
768                     }
```

```
769                 std::cout << "\n----------------------------------------------------------------------------------------------------" << std
                        ::endl;
770               }
771
772               d_burst_count++; // Keeping track for statistics
773
774               burst_search();
775               break;
776             }
777             default:
778               assert(0);
779               break;
780
781           }
782         }
783
784         if((d_debug == DebugType::PACKET_USRP_ON) || (d_debug == DebugType::ALL_ON))
785         {
786           std::cout << "------------------------------------------------------\n";
787           std::cout << "Current Preamble Sample Len: " << d_phy_802_15_4.get_preamble_len_samples() << "\n";
788           std::cout << "Current Input Size: " << ninput << "\n";
789           std::cout << "Current Burst Count: " << d_burst_count << "\n";
790           std::cout << "Current Valid Fingerprints: " << d_fingerprints_counter << "\n";
791           std::cout << "Current Invalid Fingerprints: " << d_nan_counter << "\n";
792           std::cout << "------------------------------------------------------" << std::endl;
793         }
794
795         consume(0, noutput_items);
796
797         // Tell runtime system how many output items we produced.
798         return 0;
799       }
800
801       void
802       dna_detector_ccf_impl::burst_search()
803       {
804         d_state = SEARCHING;
805         d_current_detected_preamble.clear();
806       }
807
808       void
809       dna_detector_ccf_impl::burst_detect()
810       {
811         d_state = DETECTED;
812       }
813
814       void
815       dna_detector_ccf_impl::burst_fingerprint()
816       {
817         // At this point, I need to perform RFDNA Analysis
818         //this is to get rid of the extra zeroes beyond the preamble sample size
819         if(d_current_detected_preamble.size() > d_phy_802_15_4.get_preamble_len_samples())
820         {
821           d_current_detected_preamble.resize(d_phy_802_15_4.get_preamble_len_samples());
```

```
822         }
823         d_state = FINGERPRINT;
824       }
825
826       void
827       dna_detector_ccf_impl::set_devices(const int &devices){
828         d_devices = devices;
829       }
830
831       void
832       dna_detector_ccf_impl::set_dna_row_size(const int &dna_row_size)
833       {
834         d_dna_row_size = dna_row_size;
835       }
836
837       void
838       dna_detector_ccf_impl::set_dna_column_size(const int &dna_column_size)
839       {
840         d_dna_column_size = dna_column_size;
841       }
842
843       void
844       dna_detector_ccf_impl::set_dna_region_num(const int &dna_region_num)
845       {
846         d_dna_region_num = dna_region_num;
847       }
848
849       void
850       dna_detector_ccf_impl::set_debug(const DebugType &debug)
851       {
852         d_debug = debug;
853         d_usrp_debug = (debug & USRP_ON) > 0 ? 1 : 0;
854       }
855
856       void
857       dna_detector_ccf_impl::set_dna_fingerprint_filename(const std::string &fingerprint_filename)
858       {
859         d_fingerprint_filename = fingerprint_filename;
860       }
861
862       void
863       dna_detector_ccf_impl::set_dna_fingerprint_save_switch(const SWITCH &fingerprint_save_switch)
864       {
865         d_fingerprint_save_switch = fingerprint_save_switch;
866       }
867
868       void
869       dna_detector_ccf_impl::set_dna_classification_matrix_filename(const std::string &class_matrix_filename)
870       {
871         d_class_matrix_filename = class_matrix_filename;
872       }
873
874       void
875       dna_detector_ccf_impl::set_dna_means_matrix_filename(const std::string &means_matrix_filename)
```

```
876     {
877       d_means_matrix_filename = means_matrix_filename;
878     }
879
880     void
881     dna_detector_ccf_impl::set_dna_classification_load_switch(const SWITCH &class_matrix_load_switch)
882     {
883       d_class_matrix_load_switch = class_matrix_load_switch;
884     }
885
886     void
887     dna_detector_ccf_impl::set_save_stats_switch(const SWITCH &save_stats_switch)
888     {
889       d_save_stats_switch = save_stats_switch;
890     }
891
892     void
893     dna_detector_ccf_impl::set_save_dna_results_switch(const SWITCH &save_dna_results_switch)
894     {
895       d_save_dna_results_switch = save_dna_results_switch;
896     }
897
898     void
899     dna_detector_ccf_impl::set_dna_norm_vector_filename(const std::string &norm_vector_filename)
900     {
901       d_norm_vector_filename = norm_vector_filename;
902     }
903
904     void
905     dna_detector_ccf_impl::set_dna_xoffset_vector_filename(const std::string &xoffset_vector_filename)
906     {
907       d_xoffset_vector_filename = xoffset_vector_filename;
908     }
909
910     void
911     dna_detector_ccf_impl::set_samp_rate(const float &samp_rate)
912     {
913       d_samp_rate = samp_rate;
914     }
915
916     int
917     dna_detector_ccf_impl::get_devices() const
918     {
919       return d_devices;
920     }
921
922     int
923     dna_detector_ccf_impl::get_dna_row_size() const
924     {
925       return d_dna_row_size;
926     }
927
928     int
929     dna_detector_ccf_impl::get_dna_column_size() const
```

```
930     {
931       return d_dna_column_size;
932     }
933
934     int
935     dna_detector_ccf_impl::get_dna_region_num() const
936     {
937       return d_dna_region_num;
938     }
939
940     DebugType
941     dna_detector_ccf_impl::get_debug() const
942     {
943       return d_debug;
944     }
945
946     std::string
947     dna_detector_ccf_impl::get_dna_fingerprint_filename() const
948     {
949       return d_fingerprint_filename;
950     }
951
952     SWITCH
953     dna_detector_ccf_impl::get_dna_fingerprint_save_switch() const
954     {
955       return d_fingerprint_save_switch;
956     }
957
958     std::string
959     dna_detector_ccf_impl::get_dna_classification_matrix_filename() const
960     {
961       return d_class_matrix_filename;
962     }
963
964     std::string
965     dna_detector_ccf_impl::get_dna_means_matrix_filename() const
966     {
967       return d_means_matrix_filename;
968     }
969
970     SWITCH
971     dna_detector_ccf_impl::get_dna_classification_load_switch()const
972     {
973       return d_class_matrix_load_switch;
974     }
975
976     SWITCH
977     dna_detector_ccf_impl::get_save_stats_switch() const
978     {
979       return d_save_stats_switch;
980     }
981
982     SWITCH
983     dna_detector_ccf_impl::get_save_dna_results_switch() const
```

```
984     {
985       return d_save_dna_results_switch;
986     }
987
988     float
989     dna_detector_ccf_impl::get_samp_rate() const
990     {
991       return d_samp_rate;
992     }
993
994     std::string
995     dna_detector_ccf_impl::get_dna_norm_vector_filename() const
996     {
997       return d_norm_vector_filename;
998     }
999
1000    std::string
1001    dna_detector_ccf_impl::get_dna_xoffset_vector_filename() const
1002    {
1003      return d_xoffset_vector_filename;
1004    }
1005
1006    float
1007    dna_detector_ccf_impl::constrain_angle(const float &angle)
1008    {
1009      float x = fmod(angle + M_PI, 2*M_PI);
1010      if(x < 0)
1011      {
1012        x += 2*M_PI;
1013      }
1014
1015      return x - M_PI;
1016    }
1017
1018    float
1019    dna_detector_ccf_impl::angle_conv(const float &angle)
1020    {
1021      return fmod(constrain_angle(angle), 2*M_PI);
1022    }
1023
1024    float
1025    dna_detector_ccf_impl::angle_diff(const float &angle_a, const float &angle_b)
1026    {
1027      float dif = fmod(angle_b -angle_a + M_PI, 2*M_PI);
1028
1029      if(dif < 0)
1030      {
1031        dif += (2*M_PI);
1032      }
1033      return std::move(dif - M_PI);
1034    }
1035
1036    float
1037    dna_detector_ccf_impl::unwrap_phase(const float &prev_angle, const float &current_angle)
```

```
1038    {
1039      return std::move(prev_angle - angle_diff(current_angle, angle_conv(prev_angle)));
1040    }
1041
1042    std::vector<float>
1043    dna_detector_ccf_impl::calculate_fingerprints(const std::vector<gr_complex> &burst)
1044    {
1045      // Assuming that the sampling rate is @ 4MS/s, then there should be 640 samples.
1046      // That preamble will be broken down into 64-samples analyzing the variance, phase,
1047      // and frequencies variance, skew, and kurtosis such that 9-samples will be produced for
1048      // every 64-samples.
1049      //
1050      //            Amplitude                    Phase(rads)                  Frequency(rads/sec)
1051      // [Variance, Skewness, Kurtosis] [Variance, Skewness, Kurtosis] [Variance, Skewness, Kurtosis]
1052      //
1053      // For example, if each returning block of 9-samples represents 1-subregion and 10-subregion represents a fingerprint
1054      // i.e. 90-samples returned @ 4MS/sec
1055
1056      std::vector<float> fingerprint;
1057      int sub_samples = d_phy_802_15_4.get_preamble_len_samples()/d_dna_region_num;
1058
1059      std::vector<gr_complex>::const_iterator i;
1060      std::vector<float> subregion_temp;
1061      for(int c = 0; c < d_dna_region_num; c++)
1062      {
1063        i = burst.begin(); //setting the itterator to the beginning of the burst
1064
1065        // Next, the itterator will be offset by a multiple of the subregion size
1066        // based on the sample rate and passed into an rvalue vector to make
1067        // the subregion
1068        subregion_temp = std::move(make_subregion(
1069                         std::vector<gr_complex>(i + sub_samples*c,
1070                         i + (c + 1)*sub_samples)));
1071
1072        // Finally, we append the sub_region to the fingerprint vector
1073        fingerprint.insert(fingerprint.end(), subregion_temp.begin(), subregion_temp.end());
1074      }
1075
1076      return std::move(fingerprint);
1077    }
1078
1079    // Accumulators and burst floats were cast to doubles for additional precision
1080    std::vector<float>
1081    dna_detector_ccf_impl::make_subregion(const std::vector<gr_complex> &burst)
1082    {
1083      std::vector<float> sub_region;
1084      std::vector<double> temp_phase;
1085
1086      // complex data was converted to doubles for statistical calculations
1087      // for additional precision
1088      std::vector<dna_marker<double>> stats;
1089      for(int c = 0; c < 3; c++)
1090      {
1091        stats.push_back(std::move(dna_marker<double>()));
```

```
1092        }
1093
1094        // prev_phase and unwrapped phase will be used to keep
1095        // track of how many times the IQ unit circle has been
1096        // traversed
1097        double prev_phase = 0.0;
1098        double unwrapped_phase = 0.0;
1099        for(std::vector<gr_complex>::size_type i = 0; i != burst.size(); i++)
1100        {
1101          unwrapped_phase = unwrap_phase(prev_phase, std::arg(burst[i]));
1102          stats[0](std::abs(burst[i]));
1103          stats[1](unwrapped_phase);
1104          stats[2](d_samp_rate * (unwrapped_phase - prev_phase));
1105          prev_phase = unwrapped_phase;
1106        }
1107
1108        // After all the processing is done, 9-samples (3 per feature) will be pushed
1109        // onto the vector and returned.  Each output was cast back to floats after
1110        // all of the statistics were tabulated
1111        for(int c = 0; c < stats.size(); c++)
1112        {
1113          sub_region.push_back(variance(stats[c]));
1114          sub_region.push_back(skewness(stats[c]));
1115          sub_region.push_back(kurtosis(stats[c]));
1116        }
1117
1118        return std::move(sub_region);
1119      }
1120
1121      std::vector<float>
1122      dna_detector_ccf_impl::fingerprint_emitter(const std::vector<float> &fingerprint)
1123      {
1124        std::vector<float> emitter_results;
1125
1126        auto fingerprint_vector = EigRowVec<float>::Map(fingerprint.data(), fingerprint.size());
1127        auto adjusted_fingerprint_vector = fingerprint_vector - d_xoffset_vector;
1128        auto results =  (adjusted_fingerprint_vector.cwiseProduct(d_norm_vector))* d_dna_matrix;
1129
1130        for(int c = 0; c < d_devices; c++)
1131        {
1132          // using Euclidiean distance, c = (a^2 - b^2)^.5,
1133          // by pulling a row of the means matrix that corresponds to each device,
1134          // perform an element-wise difference and squaring of the differences,
1135          // summing the squared difference results, and finally getting the root
1136          // of the sum.
1137          auto row_diff = d_class_means_matrix.row(c) - results;
1138          auto row_squared = row_diff.cwiseProduct(row_diff);
1139          auto row_sum = row_squared.rowwise().sum();
1140          auto row_sqrt = row_sum.cwiseSqrt();
1141          auto row_results = row_sqrt.value();
1142
1143          emitter_results.push_back(row_results);
1144        }
1145
```

```
1146         return std::move(emitter_results);
1147       }
1148
1149       void
1150       dna_detector_ccf_impl::clear_stream()
1151       {
1152         d_msg_stream.str(std::string());
1153       }
1154     } /* namespace ieee802_15_4 */
1155   } /* namespace gr */
```

D.2.2 Dna detector ccf XML GRC Code.

```
1  <?xml version="1.0"?>
2  <block>
3    <name>Dna detector ccf</name>
4    <key>ieee802_15_4_dna_detector_ccf</key>
5    <category>[IEEE802_15_4]</category>
6    <import>import ieee802_15_4</import>
7    <make>ieee802_15_4.dna_detector_ccf($devices, $dna_row_size, $dna_col_size, $dna_region_num,
8                                        $debug, $samp_rate, $fingerprint_filename,
9                                        $fingerprint_save_switch, $class_matrix_filename,
10                                       $means_matrix_filename, $norm_vector_filename,
11                                       $xoffset_vector_filename, $class_matrix_load_switch,
12                                       $save_stats_switch, $dna_save_switch)</make>
13     <param>
14       <name>Num of Devices</name>
15       <key>devices</key>
16       <type>int</type>
17     </param>
18     <param>
19       <name>DNA File Row Size</name>
20       <key>dna_row_size</key>
21       <type>int</type>
22     </param>
23     <param>
24       <name>DNA File Col Size</name>
25       <key>dna_col_size</key>
26       <type>int</type>
27     </param>
28     <param>
29       <name>Number of Regions</name>
30       <key>dna_region_num</key>
31       <type>int</type>
32     </param>
33     <param>
34       <name>Debug</name>
35       <key>debug</key>
36       <type>enum</type>
37       <option>
38         <name>ALL_OFF</name>
39         <key>0</key>
```

```
40          </option>
41          <option>
42            <name>CHIP_ON</name>
43            <key>1</key>
44          </option>
45          <option>
46            <name>PACKET_ON</name>
47            <key>2</key>
48          </option>
49          <option>
50            <name>USRP_ON</name>
51            <key>4</key>
52          </option>
53          <option>
54            <name>CHIP_PACKET_ON</name>
55            <key>3</key>
56          </option>
57          <option>
58            <name>CHIP_USRP_ON</name>
59            <key>5</key>
60          </option>
61          <option>
62            <name>PACKET_USRP_ON</name>
63            <key>6</key>
64          </option>
65          <option>
66            <name>ALL_ON</name>
67            <key>7</key>
68          </option>
69        </param>
70        <param>
71          <name>Samp_rate</name>
72          <key>samp_rate</key>
73          <type>float</type>
74        </param>
75        <param>
76          <name>Default Fingerprint Filename</name>
77          <key>fingerprint_filename</key>
78          <type>file_save</type>
79        </param>
80        <param>
81          <name>Save Generated Fingerprints?</name>
82          <key>fingerprint_save_switch</key>
83          <type>enum</type>
84          <option>
85            <name>OFF</name>
86            <key>0</key>
87          </option>
88          <option>
89            <name>ON</name>
90            <key>1</key>
91          </option>
92        </param>
93        <param>
```

```
94          <name>Save DNA Results?</name>
95          <key>dna_save_switch</key>
96          <type>enum</type>
97          <option>
98            <name>OFF</name>
99            <key>0</key>
100         </option>
101         <option>
102           <name>ON</name>
103           <key>1</key>
104         </option>
105       </param>
106       <param>
107         <name>Default Classification Matrix</name>
108         <key>class_matrix_filename</key>
109         <type>file_open</type>
110       </param>
111       <param>
112         <name>Default Means Matrix</name>
113         <key>means_matrix_filename</key>
114         <type>file_open</type>
115       </param>
116       <param>
117         <name>Default Norm Vector</name>
118         <key>norm_vector_filename</key>
119         <type>file_open</type>
120       </param>
121       <param>
122         <name>Default XOffset Vector</name>
123         <key>xoffset_vector_filename</key>
124         <type>file_open</type>
125       </param>
126
127
128       <param>
129         <name>Load Classification Matrix?</name>
130         <key>class_matrix_load_switch</key>
131         <type>enum</type>
132         <option>
133           <name>OFF</name>
134           <key>0</key>
135         </option>
136         <option>
137           <name>ON</name>
138           <key>1</key>
139         </option>
140       </param>
141       <param>
142         <name>Save Generated Statistics?</name>
143         <key>save_stats_switch</key>
144         <type>enum</type>
145         <option>
146           <name>OFF</name>
147           <key>0</key>
```

```
148         </option>
149         <option>
150           <name>ON</name>
151           <key>1</key>
152         </option>
153       </param>
154       <sink>
155         <name>in</name>
156         <type>complex</type>
157       </sink>
158       <source>
159         <name>dna_out</name>
160         <type>message</type>
161       </source>
162   </block>
```

D.3 DNA Buffer Class

```
1   /*************************************************************************************************************************************
        ***
2    *dna_buffer Class Definition
3   *************************************************************************************************************************************
        **/
4   /*!
5   *  Class: dna_buffer
6   *  Author: Cruz, Frankie
7   *  Description: Extended vector template to buffer input data with markers
8   *               to give a user a beginning/end of a buffer and keep track
9   *               of dna preambles
10  *  Generated: Tues Nov 20 12:10:18 2018
11  *  Modified: Dec 13 12:00:37 2018
12  *  Build Version: 1.5
13  *  Changes: -buffer will now keep an array of sample lengths to pop off
14  *            the samples once a buffer threshold has been exceeded
15  *           -fixed input error with erase_buffer_element
16  */
17  class dna_buffer
18  {
19      public:
20      /*!
21      * constructors and destructors
22      */
23      dna_buffer();
24      dna_buffer(const int &space); // constructor w/ blank space intervals
25      ~dna_buffer();
26
27      /*!
28      * copy constructors and assignment operators
29      */
30      dna_buffer(const dna_buffer &copy);
31      dna_buffer &operator=(const dna_buffer &copy);
```

```
32      dna_buffer &operator=(const std::vector<gr_complex> &copy);
33
34      /*!
35      * move constructors and assignment operators
36      */
37      dna_buffer(dna_buffer && moved);
38      dna_buffer &operator=(dna_buffer &&moved);
39      dna_buffer &operator=(std::vector<gr_complex> &&moved);
40
41
42      /*!
43      * setters
44      */
45      void set_buffer();
46      void set_spacing(const int &space); // sets spacing size
47      void unset_buffer(); // deactivates the dna_buffer and clears out values
48      void erase_buffer_element(const int &element); // wrapper for vector erase function
49      void erase_buffer_range(const int &front, const int &back); // wrapper for vector erase function
50      void insert_rear_spacing(const int &space); // inserts a given zero buffer at the end of the buffer
51      void insert_front_spacing(const int &space); // insert a given zero buffer at the front of the buffer
52      void append_burst_sample_size(const int &size); // insert the size of the sample stored
53      void pop_front_burst_samples(); // remove # of samples from the buffer and remove the element the sample size
54
55      /*!
56      * getters
57      */
58      bool is_activated() const; // returns true if the buffer is set
59      int get_space() const; // returns the spacing default
60      int get_sample_length() const; // retuns how long the buffer is in samples
61      int get_burst_length() const; // returns how many bursts are stored in the buffer
62      gr_complex operator[](const int &index) const; //get access to individual data in buffer
63      std::vector<gr_complex> get_stored_buffer() const; //returns a copy of the stored buffer
64
65      /*!
66      * append_preamble_points will be used in the case where more data has to be
67      * appended i.e. input buffer is large enough to collect more than one
68      * transmission
69      */
70      void append_buffer_data(const dna_buffer &append);
71      void append_buffer_data(const std::vector<gr_complex> &append);
72      void append_buffer_data(const gr_complex &element);
73
74      /*!
75      * store_preamble will take the input size and pointer to
76      * a vector and store it into the buffer space
77      */
78      void store_preamble_data(const int &ninput_size,
79                               const gr_complex *in_rx);
80
81      protected:
82      std::vector<gr_complex> d_buffer;
83      std::vector<int> d_sample_size_array; // keeps track of front bursts sample size
84      bool d_dna_buffer_on; // keeps track of buffer if it's on/off
85      int d_space; //default preamble spacing
```

```
86  };
87
88  /*****************************************************************************************************************************
        ***
89   *dna_buffer Source Code
90  *****************************************************************************************************************************
        **/
91  dna_buffer::dna_buffer()
92  {
93      d_dna_buffer_on = false;
94      d_space = 0;
95  }
96
97  dna_buffer::dna_buffer(const int &space)
98  {
99      d_dna_buffer_on = false;
100     set_spacing(space);
101 }
102
103 dna_buffer::~dna_buffer()
104 {
105
106 }
107
108 dna_buffer::dna_buffer(const dna_buffer &copy)
109 {
110     d_dna_buffer_on = copy.d_dna_buffer_on;
111     d_space = copy.d_space;
112     d_buffer = copy.d_buffer;
113     d_sample_size_array = copy.d_sample_size_array;
114 }
115
116 dna_buffer
117 &dna_buffer::operator=(const dna_buffer &copy)
118 {
119     if(&copy != this)
120     {
121     d_dna_buffer_on = copy.d_dna_buffer_on;
122     d_space = copy.d_space;
123     d_buffer = copy.d_buffer;
124     d_sample_size_array = copy.d_sample_size_array;
125     }
126
127     return *this;
128 }
129
130 dna_buffer
131 &dna_buffer::operator=(const std::vector<gr_complex> &copy)
132 {
133     if(copy != d_buffer)
134     {
135     d_dna_buffer_on = true;
136     d_buffer = copy;
137     }
```

```
138 }
139
140 dna_buffer::dna_buffer(dna_buffer &&moved)
141 {
142     d_dna_buffer_on = std::move(moved.d_dna_buffer_on);
143     d_space = std::move(moved.d_space);
144     d_buffer = std::move(moved.d_buffer);
145     d_sample_size_array = std::move(moved.d_sample_size_array);
146 }
147
148 dna_buffer
149 &dna_buffer::operator=(dna_buffer &&moved)
150 {
151     if(this != &moved)
152     {
153     d_dna_buffer_on = std::move(moved.d_dna_buffer_on);
154     d_space = std::move(moved.d_space);
155     d_buffer = std::move(moved.d_buffer);
156     d_sample_size_array = std::move(moved.d_sample_size_array);
157     }
158
159     return *this;
160 }
161
162 dna_buffer
163 &dna_buffer::operator=(std::vector<gr_complex> &&moved)
164 {
165     set_buffer();
166     d_buffer = std::move(moved);
167 }
168
169 void
170 dna_buffer::set_buffer()
171 {
172     d_dna_buffer_on = true;
173 }
174
175 void
176 dna_buffer::set_spacing(const int &space)
177 {
178     d_space = space < 0 ? 0 : space;
179 }
180
181 void
182 dna_buffer::unset_buffer()
183 {
184     d_dna_buffer_on = false;
185     d_buffer.clear();
186     d_sample_size_array.clear();
187 }
188
189 void
190 dna_buffer::erase_buffer_element(const int &element)
191 {
```

```
192     d_buffer.erase(d_buffer.begin() + element);
193 }
194
195 void
196 dna_buffer::erase_buffer_range(const int &front, const int &back)
197 {
198     d_buffer.erase(d_buffer.begin() + front,
199                    d_buffer.begin() + back);
200 }
201
202 void
203 dna_buffer::insert_rear_spacing(const int &space)
204 {
205     if(space >0)
206     {
207     for(int c = 0; c < space; c++)
208     {
209         d_buffer.push_back(gr_complex(0.0f, 0.0f));
210     }
211     }
212 }
213
214 void
215 dna_buffer::insert_front_spacing(const int &space)
216 {
217     if(space >0)
218     {
219     for(int c = 0; c < space; c++)
220     {
221         d_buffer.insert(d_buffer.begin(), gr_complex(0.0f, 0.0f));
222     }
223     }
224 }
225
226 void
227 dna_buffer::append_burst_sample_size(const int &size)
228 {
229     d_sample_size_array.push_back(size);
230 }
231
232 void
233 dna_buffer::pop_front_burst_samples()
234 {
235     // have to have a check to see if there's anything
236     // in the buffer or we could possibly crash everything
237     // trying to remove a non-existent array
238     if(!d_sample_size_array.empty())
239     {
240     // pop off front # samples from oldest burst in the buffer
241     d_buffer.erase(d_buffer.begin(),d_buffer.begin() + d_sample_size_array[0]);
242
243     // pop off front ofcontainer holding # of samples of previous burst
244     d_sample_size_array.erase(d_sample_size_array.begin());
245     }
```

```
246 }
247
248 bool
249 dna_buffer::is_activated() const
250 {
251     return d_dna_buffer_on;
252 }
253
254 int
255 dna_buffer::get_space() const
256 {
257     return d_space;
258 }
259
260 int
261 dna_buffer::get_sample_length() const
262 {
263     return d_buffer.size();
264 }
265
266 int
267 dna_buffer::get_burst_length() const
268 {
269     return d_sample_size_array.size();
270 }
271
272 gr_complex
273 dna_buffer::operator[](const int &index) const
274 {
275     return d_buffer[index];
276 }
277
278 std::vector<gr_complex>
279 dna_buffer::get_stored_buffer() const
280 {
281     //if the vector is empty
282     return (d_buffer.empty()) ? std::vector<gr_complex>() : d_buffer;
283 }
284
285 void
286 dna_buffer::append_buffer_data(const dna_buffer &append)
287 {
288     // function wrapper for parent class
289     append_buffer_data(append.d_buffer);
290 }
291
292 void
293 dna_buffer::append_buffer_data(const std::vector<gr_complex> &append)
294 {
295     // after checking to see if the array passed
296     // is empty, the array daty will be appended
297     // with the user defined length of empty data
298     if(!append.empty())
299     {
```

```
300     for(int i = 0; i < d_space + append.size(); i++)
301     {
302         if(i < d_space)
303         {
304         d_buffer.push_back(gr_complex(0.0f,0.0f));
305         }else{
306         //d_buffer.push_back(append[i - d_space]);
307         append_buffer_data(append[i - d_space]);
308         }
309     }
310     }
311 }
312
313 void
314 dna_buffer::append_buffer_data(const gr_complex &element)
315 {
316     d_dna_buffer_on = true; // by default, if any data is appended, then the buffer must be set
317     d_buffer.push_back(element);
318 }
319
320 void
321 dna_buffer::store_preamble_data(const int &input_size,
322                                 const gr_complex *in_rx)
323 {
324
325     // initial check to ensure that the size
326     // of the received data is worth copying
327     // before estimating the indexes
328     if(input_size > 0)
329     {
330     std::vector<gr_complex> temp; // temporary placeholder
331     set_buffer();
332
333     for(int i = 0; i < input_size; i++)
334     {
335         temp.push_back(in_rx[i]);
336     }
337
338     d_buffer = std::move(temp);
339     }
340 }
```

D.4 Base Packet and IEEE 802.15.4 Packet Classes

```
1  /*************************************************************************************************************************
       ***
2   *packet_base Class Definition
3  *************************************************************************************************************************
       **/
4  /*!
5  *  Class: packet_base
```

```
6   *  Author: Cruz, Frankie
7   *  Description: Base class interface for minimalist
8   *               PHY Packet size calculation based
9   *               on on preamble section, 1 length,
10  *               section, and 1 payload section.
11  *               Each standard breaks these three
12  *               down further into smaller subsets.
13  *  Generated: Tues  Nov 20 22:00:18 2018
14  *  Modified: Dec 01 13:30:01 2018
15  *  Build Version: 1.3
16  *  Changes: -fixed get_preamble_len_samples
17  */
18  class packet_base
19  {
20      public:
21      packet_base() = default;
22      ~packet_base() = default;
23
24      /*!
25      * Setters Interface for preamble, length,
26      * and data packet field sizes
27      */
28      virtual void set_preamble_len_bytes(const int &preamble_len){d_preamble_len = preamble_len;};
29      virtual void set_length_len_bytes(const int &length_len){d_length_len = length_len;};
30      virtual void set_data_len_bytes(const int &data_len){d_data_len = data_len;};
31
32      /*!
33      * Getters Interface for preamble, length,
34      * and data packet field sizes
35      */
36      virtual int get_preamble_len_bytes() const {return d_preamble_len;};
37      virtual int get_length_len_bytes() const {return d_length_len;};
38      virtual int get_data_len_bytes() const {return d_data_len;};
39      virtual int get_packet_len_bytes() const {return (d_preamble_len + d_length_len + d_data_len);};
40      virtual int get_preamble_len_chips() const {return round(d_byte2sym * d_sym2chip * d_preamble_len);};
41      virtual int get_length_len_chips() const {return round(d_byte2sym * d_sym2chip * d_length_len);};
42      virtual int get_data_len_chips() const {return round(d_byte2sym * d_sym2chip * d_data_len);};
43      virtual int get_packet_len_chips() const {return round(d_byte2sym * d_sym2chip * get_packet_len_bytes());};
44      virtual int get_preamble_len_samples() const {return round(d_chip_period * d_sample_rate * get_preamble_len_chips());};
45      virtual int get_length_len_samples() const {return round(d_chip_period * d_sample_rate * get_length_len_chips());};
46      virtual int get_data_len_samples() const {return round(d_chip_period * d_sample_rate * get_data_len_chips());};
47      virtual int get_packet_len_samples() const {return round(d_chip_period * d_sample_rate * get_packet_len_chips());};
48
49      /*!
50      * Setters Interface for rates and periods
51      */
52      virtual void set_chip_period(const float &chip_period);
53      virtual void set_symbol_period(const float &symbol_period);
54      virtual void set_sample_period(const float &sample_period);
55      virtual void set_chip_rate(const float &chip_rate);
56      virtual void set_symbol_rate(const float &symbol_rate);
57      virtual void set_sample_rate(const float &sample_rate);
58
59      /*!
```

```
60      * Setters Interface for conversion multipliers
61      */
62      virtual void set_byte_to_sym_mult(const float &byte2sym);
63      virtual void set_sym_to_byte_mult(const float &sym2byte);
64      virtual void set_sym_to_chip_mult(const float &sym2chip);
65      virtual void set_chip_to_sym_mult(const float &chip2sym);
66
67      /*!
68      * Getters Interface for rates and periods
69      */
70      virtual float get_chip_period() const {return d_chip_period;};
71      virtual float get_symbol_period() const {return d_symbol_period;};
72      virtual float get_sample_period() const {return d_sample_period;};
73      virtual float get_chip_rate() const {return 1/d_chip_period;};
74      virtual float get_symbol_rate() const {return 1/d_symbol_period;};
75      virtual float get_sample_rate() const {return 1/d_sample_period;};
76
77      /*!
78      * Getters Interface for conversion multipliers
79      */
80      virtual float get_byte_to_sym_mult() const {return d_byte2sym;};
81      virtual float get_sym_to_byte_mult() const {return d_sym2byte;};
82      virtual float get_sym_to_chip_mult() const {return d_sym2chip;};
83      virtual float get_chip_to_sym_mult() const {return d_chip2sym;};
84      virtual float get_bit_to_byte_mult() const {return d_bit2byte;}
85      virtual float get_byte_to_bit_mult() const {return 1/d_bit2byte;}
86
87      private:
88      int d_preamble_len = 0; // preamble frame length in bytes
89      int d_length_len = 0;   // data length field parameter in bytes
90      int d_data_len = 0; // data packet frame length in bytes
91      float d_bit2byte = 0.125f; // 1-bit is 1/8 byte (byte/bit)
92      float d_chip_period = 0.0f; // (seconds/chip)
93      float d_symbol_period = 0.0f; // (seconds/symbol)
94      float d_chip_rate = 0.0f; // (chip/sec)
95      float d_symbol_rate = 0.0f; // (sym/sec)
96      float d_byte2sym = 0.0f; // 1-byte = 2-symbols (sym/byte)
97      float d_sym2byte = 0.0f; // 1-symbol = 1/2 byte (byte/sym)
98      float d_sym2chip = 0.0f; // 1-symbol = 32-chips (chips/sym)
99      float d_chip2sym = 0.0f; // 1-chip = 1/32-symbols (sym/chip)
100     float d_sample_period = 0.0f; // (sec/sample)
101     float d_sample_rate = 0.0f; // (sample/sec)
102 };
103
104 /*************************************************************************************************************************
        ***
105  *ieee802_15_4_packet Class Definition
106 *************************************************************************************************************************
        **/
107 /*!
108 *  Class: ieee802_15_4_packet
109 *  Author: Cruz, Frankie
110 *  Description: IEEE802-15-4 class for
111 *               PHY Packet size calculation.
```

```
112  *  Generated: Tues Nov 21 2:00:18 2018
113  *  Modified: Wed Nov 28 10:30:11 2018
114  *  Build Version: 1.2
115  *  Changes: -Removed some initializing setter
116  *           -Need to improve and fix functionality
117  */
118  class ieee802_15_4_packet : public packet_base
119  {
120      public:
121
122      /*!
123      * Constructor's and Destructor
124      */
125      ieee802_15_4_packet();
126      ieee802_15_4_packet(const float &samp_rate);
127      ieee802_15_4_packet(const int &preamble_len,
128                          const int &length_len,
129                          const int &data_len,
130                          const float &samp_rate);
131      ~ieee802_15_4_packet() = default;
132
133      /*!
134      * Copy Constructor & Assignment
135      */
136      ieee802_15_4_packet(const ieee802_15_4_packet &copy);
137      ieee802_15_4_packet &operator=(const ieee802_15_4_packet &copy);
138
139      /*!
140      * Getters for bytes, chips, and samples for
141      * ieee802-15-4 packet sections
142      */
143      int get_shr_preamble_len_byte() const;
144      int get_shr_sfd_len_bytes() const;
145      int get_phr_len_bytes() const;
146      int get_payload_len_bytes() const;
147      int get_crc_len_bytes() const;
148      int get_shr_preamble_len_chips() const;
149      int get_shr_sfd_len_chips() const;
150      int get_phr_len_chips() const;
151      int get_payload_len_chips() const;
152      int get_crc_len_chips() const;
153      int get_shr_preamble_len_samples() const;
154      int get_shr_sfd_len_samples() const;
155      int get_phr_len_samples() const;
156      int get_payload_len_samples() const;
157      int get_crc_len_samples() const;
158
159      private:
160      const int d_shr_preamble_len = 4; // sync preamble (4 - 0x00 or 32-bits)
161      const int d_shr_sfd_len = 1; // start of frame delimiter (1 - 0x7A or 8-bits)
162      const int d_phr_len = 1; // phr header denoting packet length
163      const int d_payload_len = 125; // payload length (max 125-bytes or 1000-bits)
164      const int d_crc_len = 2; // crc to check packet validity
165
```

```
166 };
167
168 /**************************************************************************************************************************
        ***
169  *packet_base Source Code
170 **************************************************************************************************************************
        **/
171 void
172 packet_base::set_chip_period(const float &chip_period)
173 {
174     d_chip_period = chip_period;
175
176     if(d_chip_rate != (1/chip_period))
177     {
178     d_chip_rate = 1/chip_period;
179     }
180 }
181
182 void
183 packet_base::set_symbol_period(const float &symbol_period)
184 {
185     d_symbol_period = symbol_period;
186
187     if(d_symbol_rate != (1/symbol_period))
188     {
189     d_symbol_rate = 1/d_symbol_period;
190     }
191 }
192
193 void
194 packet_base::set_sample_period(const float & sample_period)
195 {
196     d_sample_period = sample_period;
197
198     if(d_sample_rate != (1/sample_period))
199     {
200     d_sample_rate = 1/sample_period;
201     }
202 }
203
204 void
205 packet_base::set_chip_rate(const float &chip_rate)
206 {
207     d_chip_rate = chip_rate;
208
209     if(d_chip_period != (1/chip_rate))
210     {
211     d_chip_period = 1/chip_rate;
212     }
213 }
214
215 void
216 packet_base::set_symbol_rate(const float &symbol_rate)
217 {
```

```
218         d_symbol_rate = symbol_rate;
219
220         if(d_symbol_period != (1/symbol_rate))
221         {
222         d_symbol_period = 1/symbol_rate;
223         }
224     }
225
226     void
227     packet_base::set_sample_rate(const float &sample_rate)
228     {
229         d_sample_rate = sample_rate;
230
231         if(d_sample_period != (1/sample_rate))
232         {
233         d_sample_period = 1/sample_rate;
234         }
235     }
236
237     void
238     packet_base::set_byte_to_sym_mult(const float &byte2sym)
239     {
240         d_byte2sym = byte2sym;
241
242         if(d_sym2byte != (1/byte2sym))
243         {
244         d_sym2byte = 1/byte2sym;
245         }
246     }
247
248     void
249     packet_base::set_sym_to_byte_mult(const float &sym2byte)
250     {
251         d_sym2byte = sym2byte;
252
253         if(d_byte2sym != (1/sym2byte))
254         {
255         d_byte2sym = 1/sym2byte;
256         }
257     }
258
259     void
260     packet_base::set_sym_to_chip_mult(const float &sym2chip)
261     {
262         d_sym2chip = sym2chip;
263
264         if(d_chip2sym != (1/sym2chip))
265         {
266         d_chip2sym = 1/sym2chip;
267         }
268     }
269
270     void
271     packet_base::set_chip_to_sym_mult(const float &chip2sym)
```

```
272 {
273     d_chip2sym = chip2sym;
274
275     if(d_sym2chip != (1/chip2sym))
276     {
277     d_sym2chip = 1/chip2sym;
278     }
279 }
280
281 /*************************************************************************************************************************
        ***
282  *ieee802_15_4_packet Source Code
283 *************************************************************************************************************************
        **/
284 ieee802_15_4_packet::ieee802_15_4_packet()
285 {
286     set_preamble_len_bytes(d_shr_preamble_len + d_shr_sfd_len);
287     set_length_len_bytes(d_phr_len);
288     set_data_len_bytes(d_payload_len + d_crc_len);
289     set_sample_rate(4e6f);
290     set_chip_rate(2e6f);
291     set_symbol_rate(1e6f);
292     set_byte_to_sym_mult(2.0f);
293     set_sym_to_chip_mult(32.0f);
294 }
295
296 ieee802_15_4_packet::ieee802_15_4_packet(const float &samp_rate)
297 {
298     set_preamble_len_bytes(d_shr_preamble_len + d_shr_sfd_len);
299     set_length_len_bytes(d_phr_len);
300     set_data_len_bytes(d_payload_len + d_crc_len);
301     set_sample_rate(samp_rate);
302     set_chip_rate(2e6f);
303     set_symbol_rate(1e6f);
304     set_byte_to_sym_mult(2.0f);
305     set_sym_to_chip_mult(32.0f);
306 }
307
308 ieee802_15_4_packet::ieee802_15_4_packet(const int &preamble_len,
309                                          const int &length_len,
310                                          const int &data_len,
311                                          const float &samp_rate)
312 {
313     set_preamble_len_bytes(preamble_len);
314     set_length_len_bytes(length_len);
315     set_data_len_bytes(data_len);
316     set_sample_rate(samp_rate);
317     set_chip_rate(2e6f);
318     set_symbol_rate(1e6f);
319     set_byte_to_sym_mult(2.0f);
320     set_sym_to_chip_mult(32.0f);
321 }
322
323 ieee802_15_4_packet::ieee802_15_4_packet(const ieee802_15_4_packet &copy)
```

```
{
    set_preamble_len_bytes(copy.get_preamble_len_bytes());
    set_length_len_bytes(copy.get_length_len_bytes());
    set_data_len_bytes(copy.get_data_len_bytes());
    set_sample_period(copy.get_sample_period());
    set_sample_rate(copy.get_sample_rate());
    set_chip_rate(copy.get_chip_rate());
    set_chip_period(copy.get_chip_period());
    set_symbol_period(copy.get_symbol_period());
    set_symbol_rate(copy.get_symbol_rate());
    set_byte_to_sym_mult(copy.get_byte_to_sym_mult());
    set_sym_to_byte_mult(copy.get_sym_to_byte_mult());
    set_sym_to_chip_mult(copy.get_sym_to_chip_mult());
    set_chip_to_sym_mult(copy.get_chip_to_sym_mult());
}

ieee802_15_4_packet
&ieee802_15_4_packet::operator=(const ieee802_15_4_packet &copy)
{
    //self assignment check
    if(&copy != this)
    {
    set_preamble_len_bytes(copy.get_preamble_len_bytes());
    set_length_len_bytes(copy.get_length_len_bytes());
    set_data_len_bytes(copy.get_data_len_bytes());
    set_sample_period(copy.get_sample_period());
    set_sample_rate(copy.get_sample_rate());
    set_chip_rate(copy.get_chip_rate());
    set_chip_period(copy.get_chip_period());
    set_symbol_period(copy.get_symbol_period());
    set_symbol_rate(copy.get_symbol_rate());
    set_byte_to_sym_mult(copy.get_byte_to_sym_mult());
    set_sym_to_byte_mult(copy.get_sym_to_byte_mult());
    set_sym_to_chip_mult(copy.get_sym_to_chip_mult());
    set_chip_to_sym_mult(copy.get_chip_to_sym_mult());
    }

    return *this;
}

int
ieee802_15_4_packet::get_shr_preamble_len_byte() const
{
    return d_shr_preamble_len;
}

int
ieee802_15_4_packet::get_shr_sfd_len_bytes() const
{
    return d_shr_sfd_len;
}

int
ieee802_15_4_packet::get_phr_len_bytes() const
```

```
378 {
379     return d_phr_len;
380 }
381
382 int
383 ieee802_15_4_packet::get_payload_len_bytes() const
384 {
385     return d_payload_len;
386 }
387
388 int
389 ieee802_15_4_packet::get_crc_len_bytes() const
390 {
391     return d_crc_len;
392 }
393
394 int
395 ieee802_15_4_packet::get_shr_preamble_len_chips() const
396 {
397     return round(d_shr_preamble_len *
398                  get_byte_to_sym_mult() *
399                  get_sym_to_chip_mult());
400 }
401
402 int
403 ieee802_15_4_packet::get_shr_sfd_len_chips() const
404 {
405     return round(d_shr_sfd_len *
406                  get_byte_to_sym_mult() *
407                  get_sym_to_chip_mult());
408 }
409
410 int
411 ieee802_15_4_packet::get_phr_len_chips() const
412 {
413     return round(d_phr_len *
414                  get_byte_to_sym_mult() *
415                  get_sym_to_chip_mult());
416 }
417
418 int
419 ieee802_15_4_packet::get_payload_len_chips() const
420 {
421     return round(d_payload_len *
422                  get_byte_to_sym_mult() *
423                  get_sym_to_chip_mult());
424 }
425
426 int
427 ieee802_15_4_packet::get_crc_len_chips() const
428 {
429     return round(d_crc_len *
430                  get_byte_to_sym_mult() *
431                  get_sym_to_chip_mult());
```

```
432 }
433
434 int
435 ieee802_15_4_packet::get_shr_preamble_len_samples() const
436 {
437     return round(get_shr_preamble_len_chips() *
438                  get_chip_period() *
439                  get_sample_rate());
440 }
441
442 int
443 ieee802_15_4_packet::get_shr_sfd_len_samples() const
444 {
445     return round(get_shr_sfd_len_chips() *
446                  get_chip_period() *
447                  get_sample_rate());
448 }
449
450 int
451 ieee802_15_4_packet::get_phr_len_samples() const
452 {
453     return round(get_phr_len_chips() *
454                  get_chip_period() *
455                  get_sample_rate());
456 }
457
458 int
459 ieee802_15_4_packet::get_payload_len_samples() const
460 {
461     return round(get_payload_len_chips() *
462                  get_chip_period() *
463                  get_sample_rate());
464 }
465
466 int
467 ieee802_15_4_packet::get_crc_len_samples() const
468 {
469     return round(get_crc_len_chips() *
470                  get_chip_period() *
471                  get_sample_rate());
472 }
```

D.5 File Read Implementation Class

```
1 /*************************************************************************************************************************
      ***
2  *file_read_impl Class Definition
3 *************************************************************************************************************************
      **/
4 /*!
5 *  Class: file_read_impl
```

```
6   *  Author: GNURadio; Cruz, Frankie
7   *  Description: Based off of file_source_impl
8   *               hardcoded due to time constraints.
9   *               Essentially load binary data
10  *  Generated: Thurs Dec 06 11:00:00 2018
11  *  Modified: Thurs Dec 07 10:00:00 2018
12  *  Build Version: 1.1
13  *  Changes: -added a string store & getter function
14  *            for the filename
15  *           -added getter for itemsize
16  */
17  class file_read_impl
18  {
19      private:
20      size_t d_itemsize;
21      FILE *d_fp;
22      FILE *d_new_fp;
23      bool d_repeat;
24      bool d_updated;
25      bool d_file_begin;
26      long d_repeat_cnt;
27      pmt::pmt_t d_add_begin_tag;
28      std::string d_filename; //storeage for filename
29
30      boost::mutex fp_mutex;
31      pmt::pmt_t _id;
32
33      void do_update();
34
35      public:
36      file_read_impl(const size_t &itemsize, const char *filename, const bool &repeat = false);
37      ~file_read_impl();
38
39      bool seek(long seek_point, int whence);
40      void open(const char *filename, bool repeat);
41      void close();
42
43      int read_data(const int &array_size,
44          void* read_data);
45
46      void set_begin_tag(const pmt::pmt_t &val);
47      std::string get_filename() const;
48      size_t get_size() const;
49
50  };
51
52  /*************************************************************************************************************************
        ***
53   *file_read_impl Source Code
54  *************************************************************************************************************************
        **/
55  file_read_impl::file_read_impl(const size_t &itemsize, const char *filename, const bool &repeat)
56                                  :d_itemsize(itemsize), d_fp(0), d_new_fp(0),
57                                  d_repeat(repeat),d_updated(false), d_file_begin(true),
```

```
58                                      d_repeat_cnt(0),d_add_begin_tag(pmt::PMT_NIL)
59  {
60      open(filename, repeat);
61      do_update();
62      d_filename.append(filename);
63
64      std::stringstream str;
65      //str << name() << unique_id();
66      str << "AFIT File Read!!!";
67      _id = pmt::string_to_symbol(str.str());
68  }
69
70  file_read_impl::~file_read_impl()
71  {
72      if(d_fp)
73      fclose ((FILE*)d_fp);
74      if(d_new_fp)
75      fclose ((FILE*)d_new_fp);
76  }
77
78  bool
79  file_read_impl::seek(long seek_point, int whence)
80  {
81      return fseek((FILE*)d_fp, seek_point *d_itemsize, whence) == 0;
82  }
83
84
85  void
86  file_read_impl::open(const char *filename, bool repeat)
87  {
88      // obtain exclusive access for duration of this function
89      gr::thread::scoped_lock lock(fp_mutex);
90
91      int fd;
92
93      // we use "open" to use to the O_LARGEFILE flag
94      if((fd = ::open(filename, O_RDONLY | OUR_O_LARGEFILE | OUR_O_BINARY)) < 0)
95      {
96      perror(filename);
97      throw std::runtime_error("can't open file");
98      }
99
100     if(d_new_fp)
101     {
102     fclose(d_new_fp);
103     d_new_fp = 0;
104     }
105
106     if((d_new_fp = fdopen (fd, "rb")) == NULL)
107     {
108     perror(filename);
109     ::close(fd);    // don't leak file descriptor if fdopen fails
110     throw std::runtime_error("can't open file");
111     }
```

```
112
113         //Check to ensure the file will be consumed according to item size
114         fseek(d_new_fp, 0, SEEK_END);
115         int file_size = ftell(d_new_fp);
116         rewind (d_new_fp);
117
118         //Warn the user if part of the file will not be consumed.
119         if(file_size % d_itemsize){
120         GR_LOG_WARN(d_logger, "WARNING: File will not be fully consumed with the current output type");
121         }
122
123         d_updated = true;
124         d_repeat = repeat;
125     }
126
127     void
128     file_read_impl::close()
129     {
130         // obtain exclusive access for duration of this function
131         gr::thread::scoped_lock lock(fp_mutex);
132
133         if(d_new_fp != NULL)
134         {
135         fclose(d_new_fp);
136         d_new_fp = NULL;
137         }
138         d_updated = true;
139         }
140
141     void
142     file_read_impl::do_update()
143     {
144         if(d_updated)
145         {
146             gr::thread::scoped_lock lock(fp_mutex); // hold while in scope
147
148         if(d_fp)
149             fclose(d_fp);
150
151         d_fp = d_new_fp;    // install new file pointer
152         d_new_fp = 0;
153         d_updated = false;
154         d_file_begin = true;
155         }
156     }
157
158     void
159     file_read_impl::set_begin_tag(const pmt::pmt_t &val)
160     {
161         d_add_begin_tag = val;
162     }
163
164     int
165     file_read_impl::read_data(const int &array_size,
```

```
166                                 void *read_data)
167 {
168     char *o = (char*)read_data;
169     int i;
170     int size = array_size;
171
172     do_update();        // update d_fp is reqd
173     if(d_fp == NULL)
174         throw std::runtime_error("work with file not open");
175
176     gr::thread::scoped_lock lock(fp_mutex); // hold for the rest of this function
177
178     while(size) {
179     i = fread(o, d_itemsize, size, (FILE*)d_fp);
180
181     size -= i;
182     o += i * d_itemsize;
183
184     if(size == 0)       // done
185         break;
186
187     if(i > 0)           // short read, try again
188         continue;
189
190     // We got a zero from fread.  This is either EOF or error.  In
191     // any event, if we're in repeat mode, seek back to the beginning
192     // of the file and try again, else break
193     if(!d_repeat)
194         break;
195
196     if(fseek ((FILE *) d_fp, 0, SEEK_SET) == -1) {
197         fprintf(stderr, "[%s] fseek failed\n", __FILE__);
198         exit(-1);
199     }
200
201     if (d_add_begin_tag != pmt::PMT_NIL)
202     {
203         d_file_begin = true;
204         d_repeat_cnt++;
205     }
206     }
207
208     if(size > 0)                // EOF or error
209     {
210     if(size == array_size)       // we didn't read anything; say we're done
211         return -1;
212     return array_size - size;   // else return partial result
213     }
214
215     return array_size;
216 }
217
218 std::string
219 file_read_impl::get_filename() const{
```

```
220     return d_filename;
221 }
222
223 size_t
224 file_read_impl::get_size() const
225 {
226     return d_itemsize;
227 }
```

D.6 File Store Base and File Store Implementation Classes

```
1  /*************************************************************************************************************************
       ***
2   *file_store_base Class Definition
3  *************************************************************************************************************************
       **
4  /*!
5  *  Class: file_store_base
6  *  Author: GNURadio; Cruz, Frankie
7  *  Description: Based off of file_sink_base
8  *               hardcoded due to time constraints
9  *  Generated: Thurs Dec 06 11:00:00 2018
10 *  Modified: Thurs Dec 07 10:00:00 2018
11 *  Build Version: 1.1
12 *  Changes: -added a string and getter function
13 *           for the filename
14 */
15 class file_store_base
16 {
17   protected:
18     FILE        *d_fp;        // current FILE pointer
19     FILE        *d_new_fp;    // new FILE pointer
20     bool         d_updated;   // is there a new FILE pointer?
21     bool         d_is_binary;
22     boost::mutex d_mutex;
23     bool         d_unbuffered;
24     bool         d_append;
25     std::string  d_filename; // c_string of filename
26
27   protected:
28     file_store_base(const char *filename, const bool &is_binary, const bool &append);
29
30   public:
31     file_store_base() {}
32     ~file_store_base();
33
34     /*!
35     * \brief Open filename and begin output to it.
36     */
37     bool open(const char *filename);
38
```

```
39      /*!
40      * \brief Close current output file.
41      *
42      * Closes current output file and ignores any output until
43      * open is called to connect to another file.
44      */
45      void close();
46
47      /*!
48      * \brief if we've had an update, do it now.
49      */
50      void do_update();
51
52      /*!
53      * \brief turn on unbuffered writes for slower outputs
54      */
55      void set_unbuffered(const bool &unbuffered);
56
57      /*!
58      * option to append data to file
59      */
60      void set_append(const bool &append);
61
62      std::string get_filename() const; // returns stored filename
63
64  };
65
66  /*************************************************************************************************************************
        ***
67   *file_store_impl Class Definition
68  *************************************************************************************************************************
        **/
69  /*!
70  *  Class: file_store_impl
71  *  Author: GNURadio; Cruz, Frankie
72  *  Description: Based off of file_sink_impl
73  *               hardcoded due to time constraints.
74  *               Essentially save's binary data
75  *  Generated: Thurs Dec 06 11:00:00 2018
76  *  Modified: Thurs Dec 06 11:00:00 2018
77  *  Build Version: 1.0
78  *  Changes: -Baseline
79  */
80
81  class file_store_impl : public file_store_base
82  {
83  private:
84    size_t d_itemsize;
85  public:
86    //file_read_impl will take the item_size using the sizeof() function of an int, float, gr_complex,
87    // or char.
88    file_store_impl(const size_t &itemsize, const char *filename,
89                    const bool &binary_data = true, const bool &append = false);
90    //file_store_impl(){}
```

```
91    ~file_store_impl();
92
93    int store_data(const int &array_size,
94                   void* input_items);
95
96    size_t get_size() const; // returns stored filesize
97  };
98
99  /*****************************************************************************************************************
        ***
100  *file_store_base Source Code
101 *****************************************************************************************************************
        **/
102 file_store_base::file_store_base(const char *filename, const bool &is_binary, const bool &append)
103   : d_fp(0), d_new_fp(0), d_updated(false), d_is_binary(is_binary), d_append(append)
104 {
105   if (!open(filename))
106     throw std::runtime_error ("can't open file");
107   d_filename.append(filename);
108 }
109
110 file_store_base::~file_store_base()
111 {
112   close();
113   if(d_fp) {
114     fclose(d_fp);
115     d_fp = 0;
116   }
117 }
118
119 bool
120 file_store_base::open(const char *filename)
121 {
122   gr::thread::scoped_lock guard(d_mutex);    // hold mutex for duration of this function
123
124   // we use the open system call to get access to the O_LARGEFILE flag.
125   int fd;
126   int flags;
127   if(d_append) {
128     flags = O_WRONLY|O_CREAT|O_APPEND|OUR_O_LARGEFILE|OUR_O_BINARY;
129   } else {
130     flags = O_WRONLY|O_CREAT|O_TRUNC|OUR_O_LARGEFILE|OUR_O_BINARY;
131   }
132   if((fd = ::open(filename, flags, 0664)) < 0){
133     perror(filename);
134     return false;
135   }
136   if(d_new_fp) {         // if we've already got a new one open, close it
137     fclose(d_new_fp);
138     d_new_fp = 0;
139   }
140
141   if((d_new_fp = fdopen (fd, d_is_binary ? "wb" : "w")) == NULL) {
142     perror (filename);
```

```
143       ::close(fd);        // don't leak file descriptor if fdopen fails.
144     }
145
146     d_updated = true;
147     return d_new_fp != 0;
148   }
149
150   void
151   file_store_base::close()
152   {
153     gr::thread::scoped_lock guard(d_mutex);    // hold mutex for duration of this function
154
155     if(d_new_fp) {
156       fclose(d_new_fp);
157       d_new_fp = 0;
158     }
159     d_updated = true;
160   }
161
162   void
163   file_store_base::do_update()
164   {
165     if(d_updated) {
166       gr::thread::scoped_lock guard(d_mutex);    // hold mutex for duration of this block
167       if(d_fp)
168         fclose(d_fp);
169       d_fp = d_new_fp;                      // install new file pointer
170       d_new_fp = 0;
171       d_updated = false;
172     }
173   }
174
175   void
176   file_store_base::set_unbuffered(const bool &unbuffered)
177   {
178     d_unbuffered = unbuffered;
179   }
180
181   void
182   file_store_base::set_append(const bool &append)
183   {
184     d_append = append;
185   }
186
187   std::string
188   file_store_base::get_filename() const
189   {
190     return d_filename;
191   }
192
193   /*************************************************************************************************************************
        ***
194    *file_store_impl Source Code
```

```
195 ********************************************************************************************************************************
        **/
196 file_store_impl::file_store_impl(const size_t &itemsize, const char *filename,
197                                   const bool &binary_data, const bool &append)
198                                 :file_store_base(filename, binary_data, append),
199                                   d_itemsize(itemsize)
200 {
201 }
202
203 file_store_impl::~file_store_impl()
204 {
205 }
206
207 int
208 file_store_impl::store_data(const int &array_size,
209                       void* input_items)
210 {
211   char *inbuf = (char*) input_items;
212   int  nwritten = 0;
213
214   do_update();                      // update d_fp is reqd
215
216   if(!d_fp)
217     return array_size;          // drop output on the floor
218
219   while(nwritten < array_size) {
220     int count = fwrite(inbuf, d_itemsize, array_size - nwritten, d_fp);
221     if(count == 0) {
222       if(ferror(d_fp)) {
223         std::stringstream s;
224         s << "file_sink write failed with error " << fileno(d_fp) << std::endl;
225         throw std::runtime_error(s.str());
226       }
227       else { // is EOF
228         break;
229       }
230     }
231     nwritten += count;
232     inbuf += count * d_itemsize;
233   }
234
235   if(d_unbuffered)
236     fflush (d_fp);
237
238   return nwritten;
239 }
240
241 size_t
242 file_store_impl::get_size() const
243 {
244   return d_itemsize;
245 }
```

Bibliography

1. G. Shi and K. Li, “Signal Interference in WiFi and ZigBee Networks.” New York City: Springer Publishing, 2017, ch. 2, pp. 9–28. [Online]. Available: http://link.springer.com/10.1007/978-3-319-47806-7

2. F. Eichelberger, “Using Software Defined Radio to Attack "Smart Home" Systems,” SANS Institute, Tech. Rep., 2014.

3. B. W. Ramsey, B. E. Mullins, W. M. Lowder, and R. M. Speers, “Sharpening the Stinger: Tuning KillerBee for Critical Infrastructure Warwalking,” in *IEEE Military Communications Conference*, oct 2014, pp. 104–109.

4. R. L. Security, “Killerbee IEEE 802.15.4 Research Tool.” [Online]. Available: https://github.com/riverloopsec/killerbee;http://www.riverloopsecurity.com/

5. D. W. Benjamin Ramsey, “Improved Wireless Security Through Physical Layer Protocol Manipulation and Radio Frequency Fingerprinting.”

6. A. Betances, K. M. Hopkinson, and M. D. Silvius, “Detection of Primary User Emulation Attacks Using Constellation-Based Distinct Native Attribute Techniques,” 2016.

7. T. J. Carbino, M. A. Temple, and J. Lopez, “Conditional Constellation Based-Distinct Native Attribute (CB-DNA) Fingerprinting for Network Device Authentication,” in *IEEE International Conference on Communications (ICC)*, 2016.

8. C. W. Coon, “Comparative Analysis of RF Emission Based Fingerprinting Techniques for ZigBee Device Classification, AFIT-ENG-MS-17-M-017,” Ph.D. dissertation, Masters Thesis, Air Force Institute of Technology, 2017.

9. C. Dubendorfer, “Using RF-DNA Fingerprints to Discriminate ZIGBEE Devices in an Operational Environment,” Ph.D. dissertation, Masters Thesis, Air Force Institute of Technology, 2013.

10. W. M. Lowder, “Real-Time RF-DNA Fingerprinting of ZigBee Devices Using A Software-Defined Radio with FPGA Processing, AFIT-ENG-MS-15-M-054,” Ph.D. dissertation, Masters Thesis, Air Force Institute of Technology, 2015.

11. M. Lukacs, P. Collins, and M. Temple, “Classification performance using RF-DNA fingerprinting of ultra-wideband noise waveforms,” *Electronics Letters*, vol. 51, no. 10, pp. 787–789, 2015.

12. H. Patel, M. A. Temple, and B. W. Ramsey, “Comparison of High-end and Low-end Receivers for RF-DNA Fingerprinting,” in *2014 IEEE Military Communications Conference*, oct 2014, pp. 24–29.

13. C. M. Rondeau, J. A. Betances, and M. A. Temple, “Securing ZigBee Commercial Communications Using Constellation Based Distinct Native Attribute Fingerprinting,” *Security and Communication Networks*, vol. 2018, 2018.

14. M. A. Temple, “EENG 699 - RF Fingerprinting,” p. 22, 2018.

15. D. J. Timothy Carbino, “Exploitation of Unintentional Ethernet Cable Emissions Using Constellation Based-Distinct Native Attribute (CB-DNA) Fingerprints To Enhance Network Security,” 2015.

16. C. K. Dubendorfer, B. W. Ramsey, and M. A. Temple, “An RF-DNA verification process for ZigBee networks,” in *MILCOM 2012 - 2012 IEEE Military Communications Conference*, oct 2012, pp. 1–6.

17. M. Lukacs, P. Collins, and M. Temple, “Device identification using active noise interrogation and RF-DNA "fingerprinting" for non-destructive amplifier acceptance testing,” in *IEEE 17th Annual Wireless and Microwave Technology Conference (WAMICON)*, apr 2016, pp. 1–6.

18. D. R. Reising, M. A. Temple, and M. E. Oxley, “Gabor-based RF-DNA fingerprinting for classifying 802.16e WiMAX Mobile Subscribers,” in *International Conference on Computing, Networking and Communications (ICNC)*, jan 2012, pp. 7–13.

19. B. W. Ramsey, B. E. Mullins, M. A. Temple, and M. R. Grimaila, “Wireless Intrusion Detection and Device Fingerprinting through Preamble Manipulation,” *IEEE Transactions on Dependable and Secure Computing*, vol. 12, no. 5, pp. 585–596, sep 2015.

20. Z. Alliance, “Zigbee Specification,” p. 622, 2012. [Online]. Available: http://www.zigbee.org/

21. T. W. Foundation, “Wireshark.” [Online]. Available: https://www.wireshark.org/

22. T. G. R. Foundation, “GNURadio.” [Online]. Available: https://wiki.gnuradio.org/index.php/Main_Page;https://www.gnuradio.org/doc/doxygen/index.html;https://wiki.gnuradio.org/index.php/Download;https://github.com/gnuradio/gnuradio

23. I. C. Society, *IEEE Standard for Local and metropolitan Area NetworksIEEE 802.15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)*. New York City: The Institute of Electrical and Electronics Engineers, Inc, 2011, no. September.

24. T. Schmid, “GNU Radio 802.15.4 En- and Decoding,” University of California, Los Angeles, Tech. Rep., 2007.

25. B. Sklar, *Digital Communications Fundamentals and Applications*, 2nd ed. Pearson Education, 2016.

26. S. Proakis, John G; Masoud, *Digital Communications*, 5th ed. New York City: McGraw-Hill Higher Education, 2008.

27. Reising, Donald, "Exploitation of RF-DNA for Device Classification and Verification Using GRLVQI Processing," 2012.

28. J. C. Milton, J. Susan; Arnold, *Introduction to Probability and Statistics*, 4th ed., McGraw-Hill, Ed., New York City, 2003.

29. R. Electronics, "Ramsey STE4400," 2019. [Online]. Available: http://www.ramseyelectronics.com/product.php?pid=17

30. M. Haykin, Simon;Moher, *Communication Systems*, 5th ed. Hoboken: Wiley Publishing, 2009.

31. B. G. Jacob, "Eigen." [Online]. Available: http://eigen.tuxfamily.org/index.php?title=Main_Page;http://eigen.tuxfamily.org/dox/GettingStarted.html

32. A. M. Collins, Travis F.;Getz, Robin;Pu, Di;Wyglinski, *Software-Defined Radio for Engineers*, 1st ed. Norwood: Artech House, 2018. [Online]. Available: www.artechhouse.com

33. E. R. A. N. I. Corporation, "Ettus Research." [Online]. Available: https://www.ettus.com/product/details/USRP-B205mini-i-Board;https://kb.ettus.com/Building_and_Installing_the_USRP_Open-Source_Toolchain_(UHD_and_GNU_Radio)_on_Linux

34. B. Bloessl, "gr-ieee802-15-4 GNURadio Block." [Online]. Available: https://github.com/bastibl/gr-ieee802-15-4

35. B. Bloessl, C. Leitner, F. Dressler, and C. Sommer, "A GNU Radio-based IEEE 802.15.4 testbed," *Proceedings of 12. GI/ITG KuVS Fachgespräch Drahtlose Sensornetze (FGSN 2013)*, pp. 37–40, 2013.

36. U. C. Workgroup, "Universal Serial Bus 3.1 Legacy Connectors and Cable Assemblies Compliance Document," p. 56, 2018. [Online]. Available: https://www.usb.org/sites/default/files/documents/cabconn_legacy_3_1_compliance_rev_1_1.pdf

37. B. Bloessl, "gr-foo GNURadio Block." [Online]. Available: https://github.com/bastibl/gr-foo

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704–0188

1. REPORT DATE *(DD–MM–YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From — To)*
21–03–2019	Master's Thesis	May 2017 — March 2019

4. TITLE AND SUBTITLE

Near Real-Time RF-DNA Fingerprinting for ZigBee Devices Using Software Defined Radios

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Cruz, Frankie A., Capt

5d. PROJECT NUMBER

JON# 19G211

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Institute of Technology
Graduate School of Engineering and Management (AFIT/EN)
2950 Hobson Way
WPAFB OH 45433-7765

8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT-ENG-MS-19-M-021

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Lab, AFMC
Attn: Dr. Vasu Chakravarthy
2241 Avionics Circle, Bldg 620
Wright Patterson AFB OH 45433-7765
Email: Vasu.Chakravarthy@us.af.mil, Comm: 937-713-4026

10. SPONSOR/MONITOR'S ACRONYM(S)

AFRL/RYWE

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A.
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

This work is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

14. ABSTRACT

Low-Rate Wireless Personal Area Network(s) (LR-WPAN) usage has increased as more consumers embrace Internet of Things (IoT) devices. ZigBee Physical Layer (PHY) is based on the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 specification designed to provide a low-cost, low-power, and low-complexity solution for Wireless Sensor Network(s) (WSN). The standard's extended battery life and reliability makes ZigBee WSN a popular choice for home automation, transportation, traffic management, Industrial Control Systems (ICS), and cyber-physical systems. As robust and versatile as the standard is, ZigBee remains vulnerable to a myriad of common network attacks. Previous research involving Radio Frequency-Distinct Native Attribute (RF-DNA) Fingerprinting and device discrimination has shown that bit-level WSN security can be augmented with PHY-based features. The objective of this research was to develop and implement an Radio Frequency (RF) air monitor system that classifies devices in Near Real-Time (NRT). The performance of the NRT air monitor is contrasted against previous research that utilized MATLAB-based Fingerprinting post-processing RF-DNA. The RF air monitor demonstration included collection of IEEE 802.15.4 bursts from $N_d = 10$ RZUSBsticks to assess NRT performance and effectiveness. The first set of experiments examined how well the air monitor recovered IEEE 802.15.4 data packets while fingerprinting and discriminating ZigBee devices under two distinct workloads. The second set of experiments compared predictive post-processed MATLAB RF-DNA Multiple Discriminant Analysis/Maximum Likelihood (MDA/ML) models Average Percent Correct Classification (%C) against the air monitor's observed operational %C for each RZUSBstick. The air monitor achieved an Overall Acurate Packet Reconstruction Percent (%R) $\geq$ 97.92% while correctly fingerprinting an Overall Fingerprinted Percent (%F) $\geq$ 97.48% of the transmitted IEEE 802.15.4 data packets during the trials. The air monitor achieved an overall operational %$C \approx$ 96.93% at a collected Signal-to-Noise Ratio (SNR) $\approx$ 33.571 dB, classified each RZUSBstick within 0.45 msec $\leq T_{\text{MDA}} \leq$ 1.5 msec after detection, and %C Deviation (%C_Δ) = 2.71% from the collected post-processed MDA/ML model. The results support that an RF air monitor is feasible, can be effective, and will accurately operate within predictive post-processed MATLAB model estimations.

15. SUBJECT TERMS

RF-DNA, PHY, Device Classification, ZigBee

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Maj J. Addison Betances, AFIT/ENG
U	U	U	U	197	19b. TELEPHONE NUMBER *(include area code)* (937) 255-3636 x3305;jbetance@afit.edu